Final Technical Report

External Grant Award Number:
G19AP00082

Recipient:
Board of Regents of the Nevada System of Higher Education on Behalf of The University of Nevada, Reno

Principal Investigator:
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Title:
Testing Reno-Area Basin Models with Shaking Records from Moderate Local and Regional Earthquakes

Project Term:
July 1, 2019 — June 30, 2021

NEHRP Element(s):
IMW Elements I and III.
National and regional earthquake hazards assessments;
Research on earthquake occurrence, physics, effects, impacts and risks.
Keywords: Earthquake hazards, Site effects, Basin effects, Scenario modeling, Ground motions, Seismic zonation, Engineering seismology

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number **G19AP00082**. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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Testing Reno-Area Basin Models with Shaking Records from Moderate Local and Regional Earthquakes

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TECHNICAL ABSTRACT

The complex Quaternary-Tertiary sedimentary and volcanic basins underlying the Reno-Sparks, Nevada urban area exacerbate the risks presented by the high earthquake potential of the region. The time-averaged seismic shear-wave velocity from the surface to 30 m (100 ft) depth, defined in the Building Code as Vs30, is in the United States one of the principal determinants of earthquake site-hazard classification. Over the past 20 years the University of Nevada, Reno and Optim Earth have built a database of refraction microtremor shear-wave velocity measurements made at hundreds of sites in the Reno area, many assessing the basin floor at almost 1 km depth. The database also gives Z1.0, the depth to the first occurrence of Vs = 1.0 km/s or greater, and Z2.5, the depth to Vs = 2.5 km/s. All but a few Reno-area sites have Vs30 between 260 m/s and 760 m/s, with a majority in NEHRP hazard class C. Sites that are geologically on bedrock have unexpectedly low Vs30, <760 m/s. There appear to be no geological- or soil-mapping criteria able to predict Vs30 in Nevada, consistent with previous work. Neither Vs30 nor Z1.0 can distinguish basin from bedrock sites. Measured Z1.0 varies from 0.015 km to 0.45 km; Z2.5 varies from 0.1 km to 0.9 km. The Vs30 and Z values provide a basis for estimating basin effects on earthquake shaking in the Reno metro area, using both current Ground Motion Models (GMMs) as well as 3D physics-based scenario shaking computation. Observed ground motions of the 2008 MW 4.9 Mogul earthquake in northwest Reno test the performance of three gravity derived basin geometry models of the Reno-area urban basin. Physics-based 3D waveform modeling with LLNL's SW4 code simulates ground motion from 0-3 Hz through 3D velocity models. All models lack sufficient velocity heterogeneity to reproduce recorded spectral velocity amplitudes above 1 Hz. The velocity models are too smooth and lack the scattering mechanisms that increase duration at both rock and proximal basin stations. Modeling results emphasize the strong 3D wave propagation effects of shallow seismic sources, such as the 3.6-km-deep Mogul mainshock. Eckert, Scalise, and Louie developed the Reno ShakeOut Scenario to anticipate the impacts of a moderate quake in the Reno urban area. The calculation assumes a minimum shear wave velocity (Vsmin) of 500 m/s and is accurate up to 3.125 Hz. Results indicate that there is a potential for widespread and variable ground shaking at Modified Mercalli Intensity (MMI) magnitudes between VII and VIII (very strong to severe ground shaking), with small areas achieving violent (IX and X) motions. Distributions of high shaking intensity are controlled by proximity to the rupture, geotechnical shear-wave velocity, topography; and significantly, basin geometry. This information helps improve our understanding of Reno's earthquake risk by highlighting these significant basin effects and the local variability that is likely to occur with any large seismic event.

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Introduction

This Final Technical Report presents the overall results of several studies that were partly sponsored by USGS external grant award G19AP00082 to the University of Nevada, Reno. This award provided critical support to PI John Louie, Ph.D. student Michelle Scalise, M.S. student Eric Eckert, and undergraduate interns Alex Simpson, Joe Maldonado, Eloisa Diaz-Armenta, Kevin Ramirez-Lopez, and Jacob Ortega. This support facilitated the completion of several research projects, the submittal of several manuscripts and databases for publication, and the graduation of all of these students.

The research products this project has helped to develop are listed below. The public-domain manuscripts are attached. For the journal papers that are not in the public domain (whether open-access or not), this public report can only contain the abstract and citation. These abstracts are below, and the public-domain reports follow.

Acknowledgements

Nevada ShakeZoning software development, data collection, and research were partly supported by the U.S. Geological Survey (USGS), Department of the Interior; under USGS award numbers 07HQGR0029, 08HQGR0015, 08HQGR0046, G09AP00050, G09AP00051, G10AP00002, G16AP00109, and G19AP00082 to Louie and others, and awards G11AP20022, G12AP20026, G14AP00020, and G15AP00055 to Optim. The Northern Nevada Seismic Network is supported under USGS award G10AC0090, and the Western Great Basin Seismic Network Operations are supported under USGS award number G10AC0090. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. Richard Saltus and Bob Jachens of the USGS kindly made their basin-thickness results available to us. For maintaining and distributing SW4 software versions 1.1 through 2.01, we thank the Computational Infrastructure for Geodynamics (http://geodynamics.org), which is funded by the National Science Foundation under awards EAR-0949446 and EAR-1550901.

Declaration of Potential Perceived Conflict of Interest

The ReMi shear-wave-velocity measurement technology is owned by the University of Nevada, and licensed exclusively to Optim Earth, Inc. Optim pays royalties to the University based on their commercial revenues from ReMi. As inventor of the technology, under University policy John Louie personally receives a share of those royalties.

Publications Partly Supported Through This Grant

(UNR students noted with "*".)

Eric Eckert*, Michelle Scalise*, John N. Louie, and Kenneth D. Smith, 2021, Exploring basin amplification within the Reno metropolitan area using a magnitude 6.3 ShakeOut scenario: accepted to *Bulletin of the Seismological Society of America*, 25 August, 42 pp. ***Abstract included in this report on p. 6.***

John N. Louie, Aasha Pancha, and Brendan Kissane, 2021, Guidelines and pitfalls of refraction microtremor surveys: *Journal of Seismology*, June 7, https://doi.org/10.1007/s10950-021-10020-5, open access. ***Abstract included in this report on p. 7.***

Alexander R. Simpson* and John N. Louie, 2020, Measurements and Predictions of Vs30, Z1.0, and Z2.5 in Nevada (Version 2.0), publication of the Nevada Seismological Laboratory, *Zenodo*, December 31, 28 pp. plus data and maps, http://doi.org/10.5281/zenodo.4408557. ***Full text included in this report starting on p. 14.***

Graduate Theses Partly Supported Through This Grant

Michelle E. Scalise*, 2021, Earthquake wave propagation in Nevada sedimentary basins (Order No. 28495902): *Ph.D. Thesis*, available from Dissertations & Theses @ University of Nevada Reno. (2563669998), 157 pp. ***Overall abstract on p. 8-9, and Chapter 2 and 3 abstracts included in this report on p. 10 and 11, respectively.***

Eric E. Eckert*, 2021, The Reno ShakeOut hazard scenario (Order No. 28497506): *M.S. Thesis*, available from Dissertations & Theses @ University of Nevada Reno. (2563493080), 51 pp. ***Abstract included in this report on p. 12.***

Presentations Partly Supported Through This Grant

Eric E. Eckert*, Michelle E. Dunn*, John N. Louie, and Kenneth D. Smith, 2019, Sensitivity tests of topographic effects on 3D simulated ground motions in Reno, Nevada: presented at Workshop on Numerical Modeling of Earthquake Motions: Waves and Ruptures - NMEM 2019, June 30 - July 4, Smolenice, Slovakia.

Morgan S. Stipe*, William S. Honjas*, Emily L. Maher*, Eric Eckert* and John N. Louie, 2019, Hammer-Sourced Prestack-Migrated Seismic Reflection-Refraction Fault and Cavity Imaging to >100 m Depth: presented at the American Geophysical Union Fall Meeting, San Francisco, Dec. 9, published at agu.org.

John Louie, Eric Eckert*, and Michelle E. Dunn*, 2020, Spatial statistics of densely measured seismic-velocity variations: Seismological Society of America Annual, Albuquerque, New Mexico, April 27-30. Abstract was accepted for presentation, but meeting was canceled due to COVID.

Michelle E. Dunn*, Eric Eckert*, John Louie, and Ken Smith, 2020, Updating the Reno Community Velocity Model: Seismological Society of America Annual, Albuquerque, New Mexico, April 27-30. Abstract was accepted for presentation, but meeting was canceled due to COVID.

J. N. Louie, A. R. Simpson*, and J. Ortega*, 2020, Database of geotechnical shear-wave seismic-velocity profile measurements for California and Nevada: Poster Presentation #226 at 2020 SCEC Annual Meeting.

J. N. Louie, A. R. Simpson*, and J. Ortega*, 2020, Database of geotechnical shear-wave seismic-velocity profile measurements for California and Nevada: Poster Presentation at Assoc. Engineering and Environmental Geologists AEG2020 Virtual Conference, Program with Abstracts, AEG News, 63(4), 42-43.

Eric Eckert*, Michelle Scalise*, John Louie, and Ken Smith, 2020, Exploring basin amplification within the Reno Metropolitan Area using a magnitude 6.2 ShakeOut scenario: American Geophysical Union Fall Meeting, poster S060-0014, Dec. 1-17, online at agu.org.

Dustin Barnes*, Andrew McIntyre, Sui Cheung, John Louie, Emily Hand, and Frederick C. Harris, Jr., 2021, Parallelizing the slant stack transform with CUDA: accepted for presentation at the 18th International Conference on Information Technology: New Generations (ITNG 2021), April 11-14, Las Vegas, Nevada, 5 pp.

Data Sets Publicly Archived with Assistance from This Grant

John N. Louie, 2020, ReMi Vs(z) Profile Archive (Version 2.0.0) [Data set]: *Zenodo*, http://doi.org/10.5281/zenodo.3951865. Cites all versions: DOI 10.5281/zenodo.3951864. ***Open-Access Database. Full text included in this report starting on p. 13.***

John Louie, Ronald Breitmeyer (2019): Community, Arts, and Environmental Setting of Fly Geyser, Nevada. International Federation of Digital Seismograph Networks. Dataset/Seismic Network. https://doi.org/10.7914/SN/Y6_2019

John Louie (2018): Surface-wave characterization of the SHOAL nuclear blast cavity and rubble chimney. International Federation of Digital Seismograph Networks. Dataset/Seismic Network. https://doi.org/10.7914/SN/6E_2018

John Louie (2017): Yosemite Valley Deep Refraction Microtremor. International Federation of Digital Seismograph Networks. Other/Seismic Network. https://doi.org/10.7914/SN/YB_2017

Exploring Basin Amplification Within the Reno Metropolitan Area Using a Magnitude 6.3 ShakeOut Scenario

Eric Eckert[1,2], Michelle Scalise[1], John N. Louie[1], Kenneth D. Smith[1]

[1]Nevada Seismological Laboratory, University of Nevada, Reno, NV, U.S.A
[2]Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, U.S.A.

Abstract
The Reno metropolitan area (located within the Truckee Meadows in northern Nevada) is subjected to significant seismic risk, primarily resulting from the region's proximity to the Mount Rose fault system and the urban area's presence within a large, thin (<1 km thick) sedimentary basin. Numerous paleoseismic studies have shown the system has a history of producing large Holocene earthquakes. To help explore this hazard we used SW4, a physics-based wave-equation modeling tool, to develop the Reno ShakeOut Scenario. The Scenario uses a grid with a minimum spacing of 20 m to perform a full 3D simulation for a potential magnitude 6.3 earthquake within the Mount Rose fault system. The calculation assumes a minimum shear wave velocity (Vsmin) of 500 m/s and is accurate up to 3.125 Hz. Results indicate that there is a potential for widespread and variable ground shaking at Modified Mercalli Intensity (MMI) magnitudes between VII and VIII (very strong to severe ground shaking), with small areas achieving violent (IX and X) motions. Distributions of high shaking are controlled by proximity to the rupture, geotechnical shear-wave velocity, topography; and significantly, basin geometry. Comparisons between SW4 peak ground velocity (PGV) computations, and PGV estimates calculated from the Campbell & Bozorgnia empirical ground motion model (GMM) emphasize the degree to which very thin basins may result in greater hazard than is currently predicted. This information helps improve our understanding of regional risk by highlighting these significant basin effects and the local variability that is likely to occur with any large seismic event.

Cite as:
Eric Eckert*, Michelle Scalise*, John N. Louie, and Kenneth D. Smith, 2021, Exploring basin amplification within the Reno metropolitan area using a magnitude 6.3 ShakeOut scenario: accepted to *Bulletin of the Seismological Society of America*, 25 August, 42 pp.

Guidelines and Pitfalls of Refraction Microtremor Surveys

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[(2)] *Seismologist / Geophysical Ground Investigation Manager, Aurecon, Wellington, NZ, Aasha.Pancha@aurecongroup.com*
[(3)] *CEO, Optim Earth, Inc., Reno, Nevada, USA, OptimSoftware.com*

Abstract

The geotechnical industry has widely adopted the refraction microtremor shear-wave velocity measurement technique, which is accepted by building authorities for evaluation of seismic site class around the world. Clark County and the City of Henderson, Nevada populated their Earthquake Parcel Map with over 10,000 site measurements for building code enforcement, made over a three-year period. 2D refraction microtremor analysis now allows engineers to image lateral shear-wave velocity variations and do passive subsurface imaging. Along with experience at a basic level, the ability to identify the "no energy area" and the "minimum-velocity envelope" on the slowness-frequency (*p*-*f*) image help practitioners to assess the quality of their ReMi data and analysis. Guides for grading (*p*-*f*) image quality, and for estimating depth sensitivity, velocity-depth tradeoffs, and depth and velocity resolution also assist practitioners in deciding whether their refraction microtremor data will meet their investigation objectives. Commercial refraction microtremor surveys use linear arrays, and a new criterion of 2.2% minimum microtremor energy in the array direction allows users to assess the likelihood of correct results. Unfortunately, any useful and popular measurement technique can be abused. Practitioners must follow correct data collection, analysis, interpretation, and measurement procedures, or the results cannot be labeled "refraction microtremor" or "ReMi" results. We present some of the common mistakes and provide solutions with the objective of establishing a "best practices" template for getting consistent, reliable models from refraction microtremor measurements.

Keywords: Geotechnical shear velocity, Seismic microzonation, Surface-wave dispersion, COSMOS, Best-Practices.

Article Highlights

- The Refraction Microtremor or ReMi technology provides shear wave velocity profiles useful for earthquake hazard assessment.
- Data collection and interpretation according to listed best practices provide fast and reliable site characterization.
- Optim Earth and the Univ. of Nevada adapted ReMi to characterize basins to >1 km depth, and for high-density mapping.

Cite as:

John N. Louie, Aasha Pancha, and Brendan Kissane, 2021, Guidelines and pitfalls of refraction microtremor surveys: *Journal of Seismology*, June 7, https://doi.org/10.1007/s10950-021-10020-5, open access.

Earthquake Wave Propagation in Nevada Sedimentary Basins

Scalise, Michelle Elyse. Ph.D. Thesis. University of Nevada, Reno, ProQuest Dissertations Publishing, 2021. 28495902.

Abstract

Nevada is one of the most seismically active of the U.S. states, with large active faults adjacent to urban areas on sedimentary basins posing significant seismic hazard. The frequent background seismicity also provides a natural laboratory for event discrimination and nonproliferation research. We explore the seismic wave propagation effects associated with earthquake hazard and nuclear explosion monitoring in the four independent chapters of this dissertation.

Focused in Reno, Nevada, urban ambient noise recording coupled with surface wave dispersion analysis to derive shear-wave seismic velocity profiles across the urban basin. Refraction Microtremor (ReMi) applied to long geophone arrays and extended recording times, images up to 1.7 and 3 km deep using 15- and 22-km-long geophone transects extending across the basin. Phase velocity uncertainties are 200 m/s below 1 second period and 600 m/s at longer periods. Dispersion data correlate well with adjacent smaller-scale deep ReMi surveys that imaged up to 1 km deep. Gravity derived basin thickness models correlate with the 2.0 km/s velocity boundary on the west side of the east-west oriented transect. ReMi results on the east side of Reno suggest basin depths are greater than what is modeled from gravity. Results inform future survey design and highlight the importance of linear array geometry and precise geophone spacing.

Observed ground motions of the 2008 M_w 4.9 Mogul earthquake in northwest Reno test the performance of three gravity derived basin geometry models of the Reno-area urban basin. Physics based 3D waveform modeling simulates ground motion from 0-3 Hz through 3D velocity models incorporating alternative basin geometries. The source model and seismic velocity assumptions are consistent across all models to isolate the effects of basin geometry on ground motion. Results indicate the Widmer basin model performs best near the Mogul subdivision, where it is more finely characterized and integrated with surface geological investigations. The Widmer model reproduces spectral velocity amplitudes better than the alterative models, but all lack the velocity heterogeneity to reproduce spectral velocity amplitudes above 1 Hz. The velocity models are too smooth and lack the scattering mechanisms that increase duration at both rock and proximal basin stations. Anomalous synthetic misfits near the Hidden Valley Golf course and extended observed durations suggest current basin models

insufficiently characterize the ground under the Hidden Valley subdivision. All results emphasize the strong 3D wave propagation effects of shallow seismic sources, such as the 3.6 km deep Mogul mainshock.

To investigate the wave propagation effects that generate shear energy from explosive sources, ground motions of the Source Physics Experiment are simulated from 0-5 Hz using high-performance computing and physics based 3D waveform modeling. Sensitivity tests of small-scale velocity heterogeneity represented by correlated random velocity perturbations using a Von Karman correlation function, show that the length scale and depth of scattering control the scattering efficiency. Models incorporating 3D geologic structure and small-scale 3D heterogeneity generate significant shear wave energy from isotropic sources at local distances. The small-scale heterogeneity improves the fit at high frequencies. Alternative source models test shear energy generated at the source, and scattering from lateral velocity heterogeneity is a larger contributor of shear motion at local distances (< 25 km). The 3D basin structure of Yucca Flat explains some of the inconsistent P/S ratio behavior at these distances, but cannot be fully reproduced with flat earth models.

In preparation for the final phase of the Source Physics Experiment, the Rock Valley Direct Comparison, seismicity in the Rock Valley Fault Zone is relocated to quantify location accuracy and image subsurface structure. Absolute relocations locate events with median 1.09 and 0.5 km vertical (depth) and horizontal errors, respectively. Relative relocations locate events with an average vertical error of 180 m. The relocation effort utilizes two 1D regional velocity models. Absolute relocation results indicate 1D velocity models can accurately locate shallow event above a prominent velocity interface (or refractor) but are insufficient for locating shallow events between 1.5- 2 km depth in geologic settings with strong lateral heterogeneity. Relative relocation results image fault structures of the Rock Valley Fault Zone and confirm the high angle fault geometry assumed in the Rock Valley Geologic Framework Model.

The independent studies demonstrate and quantify the challenges associated with shallow seismic sources in structurally complicated regions with strong lateral velocity heterogeneity. Results inform future earthquake hazard, event location and discrimination efforts.

Chapter 2: Analysis of the 2016 Deep ReMi Survey in Reno, NV

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[1]*Nevada Seismological Laboratory, University of Nevada, Reno, Reno, NV, USA*

[2]Aurecon

Abstract

Advancement in high-performance computing has enabled seismologists to simulate ground motion through structurally complex 3D earth models. As the bandwidth of these computations increases, it is necessary to resolve to finer scales the 3D velocity models used to simulate ground motion. Towards improving the resolution and accuracy of the Reno-Sparks community velocity model, a series of Refraction Microtremor (ReMi) lines have been collected across the urban basin. Originally designed to determine the shear-wave velocity of the upper 100 meters for geotechnical applications, ReMi surveying has been expanded to sample velocity structure to greater depths, by extending array lengths and using 120-second-long records during data analysis. Previously, this was applied to seven NEHRP-sponsored ReMi lines by Optim, mostly 3 km long, that imaged the basin floor at 0.5-1 km depth. The performance and limitations of this "Deep ReMi" technique had not yet been fully explored. In 2016, a long Deep ReMi survey was conducted, which transected Reno in a 22 km north-south trending line and a 15 km east-west trending line. These data sample deep basin velocity structure, which so far are only constrained by gravity analyses. Current models suggest the Pliocene to Quaternary lakebeds, alluvium, and outwash is underlain by Tertiary volcanic and sedimentary rocks, which are underlain by Mesozoic basement. The 2016 Deep ReMi data help constrain the thickness and shear-wave velocity of these units to build a more robust velocity model, with velocity profiles compared to adjacent Deep ReMi surveys and analyzed in the larger context of the Reno-Sparks community velocity model. These data highlight the limitations of the 2016 survey and inform future survey design. Results provide insight into the feasibility of generating new velocity models with a low-cost passive method practical for urban settings.

Chapter 3: Numerical Modeling of the 2008 Mogul Earthquake to Evaluate Basin Geometry

Michelle Scalise[1], John N. Louie[1], Kenneth D. Smith[1], Mark Williams[1]

[1]*Nevada Seismological Laboratory, University of Nevada, Reno, Reno, NV, USA*

Abstract

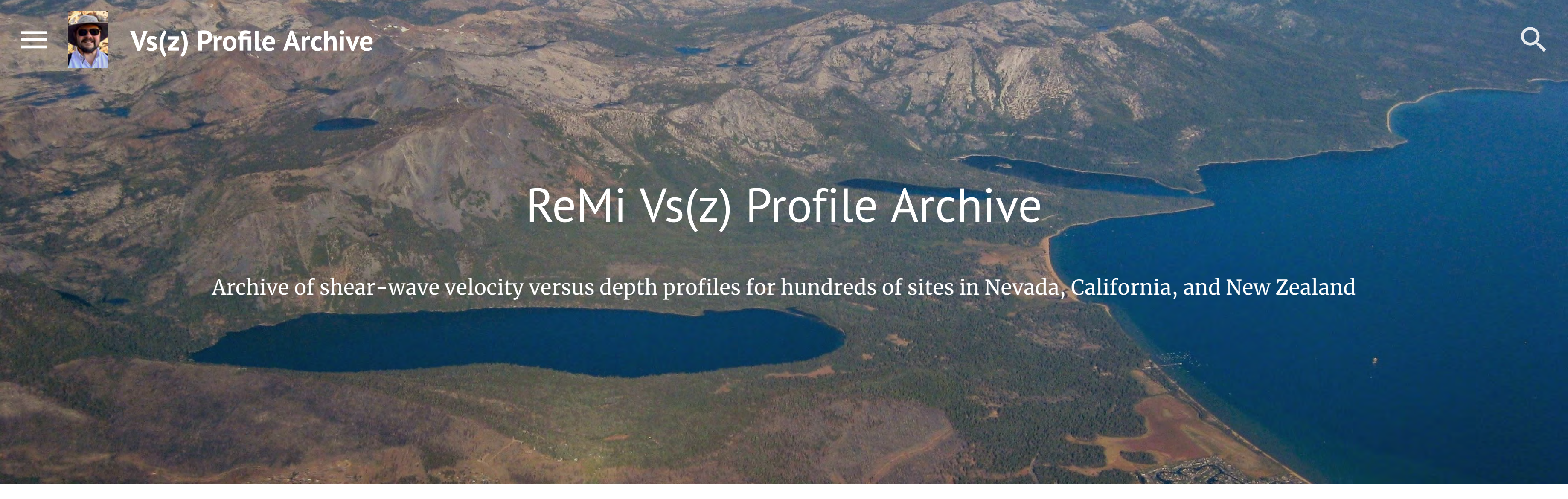
In an effort to improve deterministic ground motion modeling capabilities in the Reno urban basin, we evaluate the performance of various gravity derived basin thickness models defining large scale subsurface geometry. Simulations are computed using the 4^{th} order finite difference code SW4 on Amazon Web Services cloud computing resources from 0-3 Hz. Simulations assume identical source models, velocity and material model characteristics to isolate the effect of basin geometry on ground motion. Synthetic waveforms overproduce peak ground velocities at all seismic stations and overpredict spectral velocity amplitudes greater than 1 Hz. Results indicate a need to further refine and resolve velocity models to incorporate greater lateral and vertical velocity heterogeneity and small scale subsurface structure. Anomalous results suggest the presence of a sub-basin near the Hidden Valley subdivision that is not represented in current basin models.

The Reno ShakeOut Hazard Scenario

Eckert, Eric. University of Nevada, Reno, ProQuest Dissertations Publishing, 2021. 28497506.

Abstract

The Truckee Meadows is subjected to significant seismic risk, primarily resulting from the regions proximity to Mount Rose Fault system and the urban area's presence within a large, thin (< 1 km thick) sedimentary basin. Numerous paleoseismic studies have shown the system has a history of producing large Holocene earthquakes. To help explore this hazard we leveraged SW4, a physics-based wave-equation modeling tool, to develop the Reno ShakeOut Scenario. The Scenario is a 3.125 Hz 3D simulation for a potential magnitude 6.3 earthquake within the Mount Rose Fault system. The results indicate that there is a potential for widespread and variable ground shaking at Modified Mercalli Intensity (MMI) magnitudes between VII and VIII (very strong to severe ground shaking), with small areas achieving violent (IX and X) motions. Distributions of high shaking are controlled by proximity to the rupture, geotechnical shear-wave velocity, topography, and most significantly basin thickness. Comparisons between SW4 peak ground velocity (PGV) calculations and PGV estimates computed from the Campbell and Bozorgnia empirical ground motion model (GMM) emphasize the degree to which very thin basins may result in greater hazards than are currently predicted. This information helps improve our understanding of regional risk by highlighting these significant basin effects and the local variability that is likely to occur with any large seismic event.



ReMi Vs(z) Profile Archive

Archive of shear-wave velocity versus depth profiles for hundreds of sites in Nevada, California, and New Zealand

Archive of Publicly Sponsored Refraction Microtremor Vs(z) Results

The time-averaged seismic shear-wave velocity from the surface to 30 m (100 ft) depth, defined in the Building Code as Vs30, is in the United States one of the principal determinants of earthquake site-hazard classification. Over the past 20 years the Nevada Seismological Lab and the Applied Geophysics class at the University of Nevada, Reno; and Optim Earth have made shallow (<1 km deep) shear-wave velocity measurements at hundreds of sites in Nevada, California, and New Zealand using the ReMi technology. Many of these measurements were made at stations in regional earthquake-monitoring networks, and sponsored by the US Geological Survey. The Google Drive link leads to a directory structure grouping the measurements by region, and the files are often named with the monitoring network station name. Each file is a self-explanatory, plain-text list of the data and results from the measurement. Where multiple files are given for a particular site, measurements were made at slightly different ReMi array locations, at different times, and by different interpreters; thus expressing both the aleatory variation of velocity in the ground and the epistemic variability of the measurement technique (+/- 15% according to Louie, 2001). Each measurement file includes ReMi array location data, a summary Vs30 value, and a modeled shear-wave-velocity-versus-depth profile. Efforts are underway to add the picked ReMi p-f image and the picked fundamental-mode Rayleigh-wave dispersion-curve data to each file. Many of these measurements have been published in peer-reviewed journal papers and project reports (available in the Preprint Archive from Louie.pub). As well, these archives give additional details on ReMi measurements found in the US Geological Survey's Vs30 archive at https://earthquake.usgs.gov/data/vs30/us/ . All data in this archive are in the public domain, distributed under a Creative Commons CC BY license.

An additional 10,722 Vs30 measurements in Las Vegas and Clark County, Nevada are available from the Clark County GIS system at http://gisgate.co.clark.nv.us/ow/ (under the "hamburger" options menu select the "Seismic" map type). A Pancha et al. (2017) paper describes these measurements.

To apply the ReMi technology to your engineering project, contact Optim Earth at optimsoftware.com. For more information on ReMi applications, take a look at the draft ReMi Chapter of the COSMOS Guidelines document on surface-wave array measurement.

How To Use This Archive

Finding Vs30, Z1.0, and Z2.5

1. Within each of the geographic/project groupings below, you link into a Google Drive folder.
2. Each ReMi analysis result appears as a separate text file in your web browser, within the Google Drive interface.
3. Earthquake-monitoring site characterizations include the station code in the name of the file, so if you are looking for one of those it should be easy to find. Transect characterizations will have a site number.
4. Double-click on a file name within a folder to view or download the text file.
5. The lat/long locations of each measurement are within the text files, often along with additional location information. We are developing maps and lists to help you find sites.
6. All characterization text files have a shear-wave velocity versus depth, or Vs(z) profile. Depths and velocities are always metric, in meters and meters per second.
7. Most files give a Vs30 value; some also give Z1.0 and Z2.5 values. Some include references to the picked p-f image, and list the dispersion picks. We are in the process of populating the whole archive with those data- so let us know which sites you want us to update sooner.
8. You can determine the Vs30, and minimum possible Z1.0 and Z2.5 values from the Vs(z) profile, if the values are not given.
9. Please contact louie@seismo.unr.edu with your requests and questions.

How To Cite These Data

Louie, John N. (2020). ReMi Vs(z) Profile Archive (Version 2.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3951865

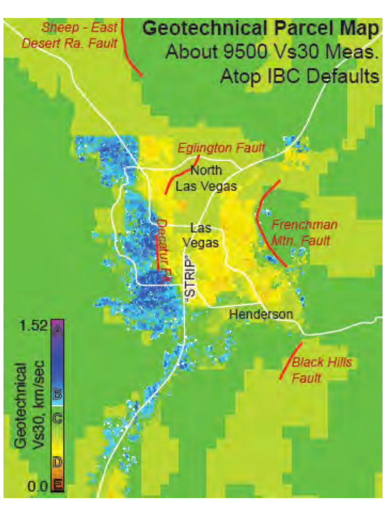
Cites all versions: DOI 10.5281/zenodo.3951864

Las Vegas

Characterization of 11 seismic monitoring sites in Las Vegas prior to the Clark County Earthquake Parcel Map.

Las Vegas Transect

Forty-nine site characterizations in a transect following the Las Vegas Strip (published).

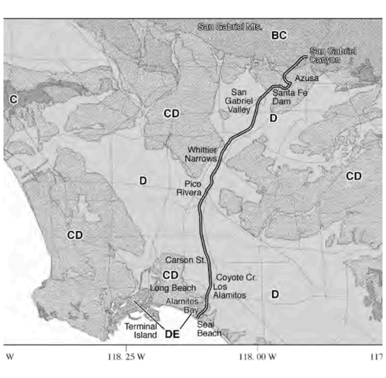


Clark Co. Parcel Map

The Clark County GIS (select "Seismic" map type) archives 10,722 ReMi Vs30 results. Final project reports to Clark Co. and Henderson. A Pancha et al. (2017) paper describes these measurements, which are not in this archive.

New Zealand

Measurements at earthquake monitoring stations in New Zealand, most in the Wellington region. A GNS Science report describes 18 additional arrays, all within the 0.7 sq.-km Parkway neighborhood of Lower Hutt City.

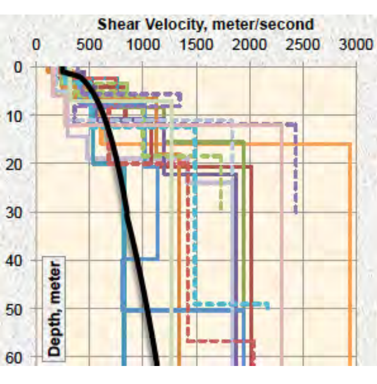


Southern California

Many ANSS seismic stations; and a transect of 200 sites following the San Gabriel River (published).

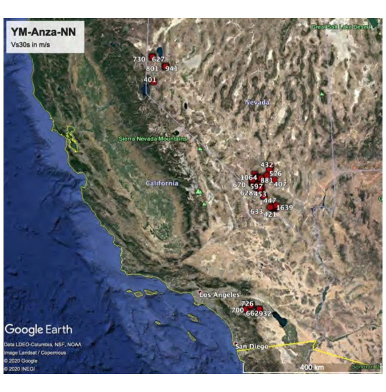
Lee Vining

Characterizations in the Long Valley Caldera area done in collaboration with UNAVCO.



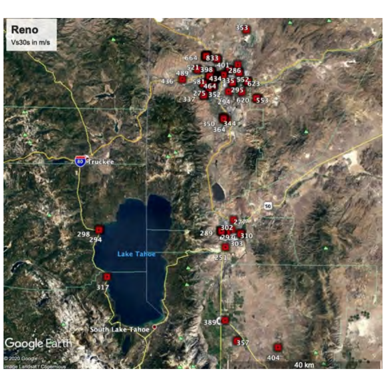
Hemet

Sites of precariously balanced rocks, identified between the San Jacinto and Elsinore faults by Prof. James Brune.



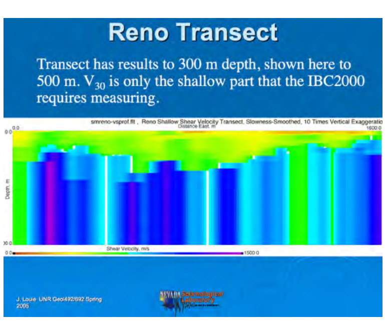
YM-Anza-NN

Sixty-one measurements at monitoring stations in the Yucca Mountain, Anza, and Northern Nevada networks. map image, kml



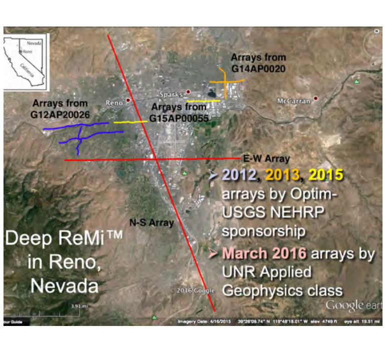
Reno, No. Nevada

ReMi characterizations of 84 seismic monitoring and strong-motion stations, and other sites in Reno-Sparks-Carson-Tahoe. map image, kml



Reno Transect

Fifty-four site characterizations in a transect following the Truckee River (published).



2017 presentation on basin effects on earthquake shaking with Steve Dickenson to Great Basin AEG

Reno Deep ReMi

108 shear-velocity profiles into basement at >1 km depth in Reno and Sparks by Optim Earth. Raw model files without explanation. More to come. (Publication on 2012 results; reports to the USGS on 2014 and 2015 results).

Additional Resources

- Summary list of 428 Vs30 values, as text, CSV, kml
- Report on "Measurements and Predictions of Vs30, Z1.0, and Z2.5 in Nevada" by Simpson and Louie, with Z1.0 and Z2.5 maps.
- John Louie website
- John Louie preprint archive
- NSZ - Nevada ShakeZoning earthquake modeling
- NSZ on YouTube
- Applied Geophysics class at UNR

COI, Acknowledgements and Disclaimers

Declaration of Potential Perceived Conflict of Interest

The ReMi technology is owned by the University of Nevada, and licensed exclusively to Optim Earth, Inc. Optim pays royalties to the University based on their commercial revenues from ReMi. As inventor of the technology, under University policy John Louie personally receives a share of those royalties.

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Disclaimers

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The information included in these documents is intended to improve earthquake preparedness; however, it does not guarantee the safety of an individual structure or facility. The State of Nevada does not assume liability for any injury, death, or property damage that occurs in connection with an earthquake.

Questions?

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<u>Measurements and Predictions of Vs30, Z1.0, and Z2.5 in Nevada</u>

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Abstract

The Nevada Seismological Laboratory has posted a public database of Refraction Microtremor (ReMi) survey results of shear-wave velocity (Vs) versus depth in the Reno-area basin, and additional locations. Most of the Vs profiles were published previously in peer-reviewed journal articles. The database collects values of Vs30, Z1.0, and Z2.5 measured at 170 sites throughout the basin. Vs30 is the time-averaged Vs between the surface and 30 m depth. Z1.0 is the depth to the first occurrence of Vs = 1.0 km/s or greater, and Z2.5 is the depth to Vs = 2.5 km/s. The database contains many more Reno-area sites with Vs30 measurements that did not also have a Z1.0 measurement; this report does not examine sites without Z1.0 values.

All but a few sites have Vs30 between 260 m/s and 760 m/s, with a majority in NEHRP hazard class C. Sites that are geologically on bedrock have unexpectedly low Vs30, <760 m/s. Intensive surveying of bedrock sites shows extreme lateral variability of Vs30 as well as Z depths, with great variations over 20 m distances due to differential weathering of volcanic rocks. There appear to be no geological- or soil-mapping criteria able to predict Vs30 in Nevada, consistent with previous work. Neither Vs30 nor Z1.0 can distinguish basin from bedrock sites in Nevada. Basin sites may well have faster Vs30 measurements than nearby bedrock sites. Some bedrock sites have Z1.0 >0.1 km, and some basin sites have Z1.0 <0.05 km. In the Reno area, measured Z1.0 varies from 0.015 km to 0.45 km; Z2.5 varies from 0.1 km to 0.9 km. The ratio of Z2.5/Z1.0 is established with a minimum of 1.0, and with some sites exhibiting a ratio as high as 4.5. In 49 Las Vegas measurements along Las Vegas Blvd., Z1.0 varies from 0.05 to 0.68 km; Z2.5 measurements are not available. Z1.0 is typically between 0.05 km and 0.11 km. Variations are likely due to highly variable occurrence of Tertiary caliche cementation.

Comparing the Vs30 and Z values to gravity-derived basin depths (Zg) correlates the depths and allows development of a practical approach for estimating Z1.0 and Z2.5 using ReMi or gravity data. Applying the models to gravity results for the Reno-area basin, Las Vegas Valley, and much of the Great Basin in Nevada and Eastern California produces maps of predicted Z1.0 in Reno only, and Z2.5 for wider areas, with reasonable results but large uncertainties. The Vs30 and Z values provide a basis for estimating basin effects on earthquake shaking throughout Nevada and Eastern California using current Ground Motion Models (GMMs), an important consideration for seismic design and performance assessment of major civil infrastructure and lifelines throughout the region.

Introduction

In the United States, the time-averaged seismic shear-wave velocity between the surface and a depth of 30 m (Vs30) is a principal predictor of site effects on the intensity of earthquake shaking (BSSC, 2020). In searching for additional site-dependent factors affecting earthquake shaking, the depths at which the seismic shear-wave velocity property (Vs) reaches 1.0 km/s (Z1.0) and 2.5 km/s (Z2.5) appear to be related to shaking intensity and duration at sites in California and Japan (Campbell and Bozorgnia, 2013). These Z values correlate to the thicknesses of soft basin-fill clastic and volcanic sediments that amplify and prolong earthquake shaking, as demonstrated in Nevada by Flinchum et al. (2014).

Reducing the geographic bias toward California and Japan in Campbell and Bozorgnia's (2013) NGA West2 database of Vs30, Z1.0, and Z2.5 would allow development of better ground-motion prediction equations (GMPEs) for a wider variety of locations. The Nevada Seismological Laboratory has for the past two decades been making surface-wave measurements at hundreds of sites in Nevada, and many hundreds more around the world. Vs30 as well as the Z values are found by conducting Refraction Microtremor (a.k.a., ReMi) seismic surface-wave surveys and producing velocity-versus-depth models. The Lab has collected together a new database of Vs measurements (Louie, 2020a), most previously published. We have added additional measurements appearing in research reports to sponsors, and some not otherwise published. This database is particularly rich in the relatively small Reno-area basin, where 170 sites all across the urban basin have Vs30 and Z1.0 measurements, and 107 of those sites have Z2.5 measurements. With these data, we can now examine the relationships between site velocity and depth properties, supplementing the NGA West2 database with abundant data from a new geography.

Most areas of Nevada, and the USA, lack detailed shear-wave measurements. This is particularly true of rapidly urbanizing exurbs on the fringes of growing metropolises such as Reno or Las Vegas. Since 1970, Nevada's population has grown from under half a million to over three million. Estimates of basin-fill thicknesses derived from gravity data are more likely to exist, with much more of the state, and country, covered by gravity surveys than by near-surface (i.e., depths of geotechnical interest) seismic surveys. A technique to predict Z1.0 and Z2.5 from gravity data would be helpful for identifying regions that warrant basin-specific seismic surveys for engineering use on critical projects (BSSC, 2020; Campbell and Bozorgnia, 2013).

Methods

ReMi measurements of Vs– Vs30 together with Z1.0, and often Z2.5, were measured at 170 locations in Reno, Nevada, within the large new database of Refraction Microtremor (ReMi) seismic survey results (Louie, 2020a). The database contains hundreds more Reno-area sites with Vs30 measurements that did not also have a Z1.0 measurement; this report does not examine sites without Z1.0 values. The great majority of the shear-wave velocity versus depth profiles we used in this analysis have been published previously in peer-reviewed journals (Scott et al., 2004; Pancha et al., 2006; Pancha et al., 2017b) or in publicly available research reports to the US Geological Survey (Louie et al., 2009; Pancha et al., 2011; Pancha and Pullammanappallil, 2014; Pullammanappallil, 2016).

The ReMi measurement method collects microtremor noise along a linear array of vertical geophones, transforms the time-distance seismic records to the slowness-frequency domain, interprets the fundamental-mode Rayleigh phase-velocity dispersion curve at the lowest possible apparent velocity at each frequency, and then forward-models a 1D Vs-versus-depth profile to fit the picked dispersion (Louie, 2001). Available images of ReMi slowness-frequency spectra and picked dispersion-curve data are actively being added to the Louie (2020a) database. Vs30 values are computed for each site from the modeled shear-wave velocity-versus-depth profiles using the time-averaging method given in the NEHRP provisions of the Building Code (BSSC, 2020). In typical commercial geotechnical application, the array of 12, 4.5 Hz geophones is 88-110 m long, dispersion picks can be made between 4 and 25 Hz, and the depth of velocity constraint is derived from the dispersion-modeling process and usually 30-100 m.

Depth of velocity constraint– The maximum depth of velocity constraint is individually analyzed and modeled for every Vs profile in the Louie (2020a) database. In Reno, various practices of ReMi surveying have resulted in depths of constraint varying from 14 m to over 2.5 km. While most database entries have a depth of constraint between 50 and 100 m, Scott et al. (2004) used 300 m arrays to measure 54 Vs soundings in Reno with depths of constraint exceeding 100 m, exceeding 300 m at faster sites. Pancha and Pullammanappallil (2014), Pullammanappallil (2016), and Pancha et al. (2017b) made 106 "deep ReMi" soundings in the Reno basin in the Louie (2020a) database, using arrays up to 6 km long resulting in dispersion picks at frequencies as low as 0.3 Hz, yielding depths of constraint of 1.0 km or more. In Las Vegas, Nevada, Scott et al. (2006) made 49 soundings in Las Vegas with 300 m array lengths, resulting in depths of constraint exceeding 100 m, in some cases exceeding 300 m.

Measuring Z1.0 and Z2.5– For each shear-wave velocity versus depth profile in the database, if the Vs value reached at least 80% of 1.0 km/s (0.80 km/s) at some depth, that depth was assigned to Z1.0 for that measurement site. Likewise, if the Vs reached at least 80% of 2.5 km/s (2.0 km/s) at some depth, then Z2.5 was interpreted to be at that depth. ReMi surveys can have ±30% velocity uncertainty for individual layer velocities in the Vs versus depth model, particularly for the deeper layers (Louie, 2001). The uncertainty in time-averaged velocities such as Vs30 is less; ±15%. Thus, we interpret a Z value at the depth where the modeled velocity only reaches 80% of the threshold velocity. As a result, Z values reported in the Louie (2020a) database may be regarded statistically as minimum Z values. If the Vs in a site's profile never reaches at least 80% of the threshold velocity, then the Z value is noted to be greater than the depth of constraint posted for that profile.

Sites without Z1.0 measurements not discussed here– The interpreted Z1.0 and Z2.5 values and the measurement locations were loaded into MATLAB for analysis along with the Vs30 reported for each measurement. Table 1 lists all 170 Vs30, Z1.0, and Z2.5 data points for Reno. Only results from surface-wave measurements in Reno where seismic shear-wave velocities reached at least 80% of 1.0 km/s and 2.5 km/s were used, numbering 170 for Z1.0 and 107 for Z2.5 in total.

Finding nearby gravity data for basin thickness– Using the Abbott and Louie (2000) gravity dataset, the nearest gravity measurement of basin-fill thickness Zg to each Vs measurement was found. As discussed by Langenheim et al. (2001) and Pancha et al. (2017b), a basin-thickness measure derived from gravity analyses ought to correlate with Z2.5 in most sedimentary basins. Since the grid spacing of Abbott and Louie (2000) was 0.4 km, any Vs measurement that was more than 0.5 km away from a Zg (gravity basin-depth value) value of >0.01 km had its Zg value set to zero. Out of 170 measurements, 23 had their Zg reduced to zero for Z1.0, and only one measurement had its Zg reduced to zero for Z2.5.

Cross-plots– Figure 1 shows a cross-plot of the Vs30 value against Z1.0 value measured at each of 170 sites in the Reno-area basin. Figure 2 shows the cross-plot of the measured Z1.0 against Z2.5 for 107 of these Reno sites. Graphs of Z1.0 versus Zg and Z2.5 versus Zg for Reno appear in Figures 3 through 10. We created approximate empirical models to predict Z1.0 and Z2.5 from Zg, in MATLAB using its curve-fitting tool. Exponential and linear models with coefficient confidence intervals of 95% were derived using least-squares fits to the data in Figures 3 through 10. Two models were determined to predict Z1.0, and two for Z2.5, an exponential and linear model each. The models, and their minimum and maximum bounds from the coefficient intervals, were plotted over the cross-plots, and they fit the data reasonably (Figures 3-6).

Additional gravity data sets– The nearest-neighbor fits to determine Zg for each seismic station were also performed with other Reno gravity data sets: a gravity data set surveyed for Reno by Washoe County (Widmer, 2005; Widmer et al., 2007; Cashman et al., 2012); and a US Geological Survey gravity inversion for clastic and volcanic basin-fill thickness across the entire Basin and Range by Saltus and Jachens (1995). Since the grid spacing for Saltus and Jachens (1995) is 2 km, any Vs measurement more than 1.5 km from a gravity measurement had its Zg from these region-wide data set to zero. There were only eight Vs measurement sites for Z1.0 that had their Widmer Zg reduced to zero. All four models were applied to cross-plots of Z1.0 or Z2.5, for the Abbott, Widmer, and Jachens data all on one graph

(Figures 7-10). The exponential models for both Z1.0 and Z2.5 from Zg fit the Reno data most favorably. Extrapolating the models derived for Reno allows at least Z2.5 to be roughly estimated elsewhere in the Great Basin, where gravity results can provide a Zg value.

Results and Discussion

Observations on the measured Vs profiles– Out of the 170 Vs30 measurements in Reno that appear in Table 1 and Figure 1, only a few have Vs30 values below 260 m/s. These measurements appear here only by virtue of being at a site having a measured value of Z1.0. There are many additional measurements of Vs30 in the Reno area appearing in the Louie (2020a) database that show values below 260 m/s. These are not discussed here because they did not also provide a measurement of Z1.0. Their depth of constraint was evidently less than Z1.0. This is true of most commercial ReMi measurements in soft sediments, which typically have a depth of constraint of only 50 m. As an extreme example, series of ReMi measurements in a hot-spring marsh in the Black Rock Desert north of Reno reliably exhibited Vs30 values as low as 81 m/s (and depths of constraint of only 30 m).

Perhaps more of a surprise is that only one of the Reno-area ReMi measurements in Table 1 and Figure 1 shows a Vs30 value above 760 m/s. This Vs30 value is the boundary between NEHRP Class C "Very dense soil and soft rock" and Class B "Rock". Table 1 shows many more "rock site" measurements, having very small Z1.0 depths, but all of these sites show measured Vs30 values below 760 m/s. As Pancha et al. (2007) discussed, all of the seismic recording stations in the Reno area that should be rock sites, have Vs30 values measured to be less than 760 m/s.

Pancha et al. (2007) investigated among others the seismic recording station at "SWTP" on the east side of the Reno-area basin, frequently used as a rock site when investigating basin amplification of earthquake shaking in Reno. Their SWTP measurement in Table 1 has a Vs30 of 731 m/s and a Z1.0 of 119 m. The follow-up SWTP-RS measurement by Pancha et al. (2011), also in Table 1, has a Z1.0 of just 7 m, but a Vs30 of 552 m/s. This measurement is just 20 m away from the Pancha et al. (2007) measurement, on colluvium over hard andesite. The very different Vs30 and Z1.0 measurements reflect the extremely rapid spatial variation of shear-wave velocity in the deeply weathered volcanic-rock masses that form the bedrock in much of the Reno area. Despite this extreme spatial variation, rock sites in the Reno area reliably show Vs30 values below 760 m/s, in the NEHRP C site class (Figure 1).

The highest Vs30 value in Table 1 and Figure 1 is from the VSTA2 site in north Reno, also on the local Miocene andesite bedrock. With a Z1.0 of 26 m, it has a Vs30 of 833 m/s. Pancha et al. (2008) investigated an adjacent site (RFNV in Table 1) extensively with ReMi recordings. As a follow-up study, the Nevada Seismological Lab deployed a series of ReMi arrays within 200 m of RFNV in close proximity to each other, and at different orientations. These results appear in Table 1 as the VSTA measurements. The VSTA arrays are all very close to each other. As at SWTP, the RFNV and VSTA measurements reflect the extreme lateral velocity variations in the heavily weathered bedrock typical of the Reno area.

Z1.0–Vs30, and Z2.5 characteristics– In Figure 1, one would expect Z1.0 to be negatively correlated with Vs30. As the average shear-wave velocity to 30 m depth increases, one might expect the depth to a velocity of 1.0 km/s to become shallower. Figure 1 does appear to show such a negative trend, a line sloping steeply down to the right. But this trend appears as an upper limit for the points in the plot. Below this limit, Z1.0 can take almost any value, even less than 30 m.

One such extreme example is a site on the eastern margin of the Reno-area basin, published by Scott et al. (2004). At this site on Cleanwater Way where it crosses Steamboat Creek, Vs = 166 m/s between the marsh at the surface down to 8 m depth, increases to 276 m/s, and then at only 15 m depth sees the 940 m/s andesite bedrock, the basin edge. Thus, this site (131-145-284.txt in Table 1 and the Louie, 2020a database) yields a measured Vs30 of 330 m/s and a Z1.0 of 0.015 km. At this low Vs30 value, Figure 1 suggests the down-to-the-right sloping trend of the Z1.0 upper limit would yield a maximum Z1.0 of 0.5 km.

Figure 2, the cross-plot of Z1.0 against Z2.5, suggests a more predictable relationship between the two depth measurements in Reno. Reno is underlain by several small, shallow sub-basins, each several kilometers wide, and generally 0.5 km to 1.2 km deep at maximum (Abbott and Louie, 2000). Pancha et al. (2017b) demonstrate with deep ReMi measurements that the basin floor, even at >0.5 km depth, may dip at greater than 45°. With basins this small, and basin-floor dips this steep, Figure 2 should not be expected to yield a sensible average or standard deviation for Z1.0 or Z2.5. The Z depths will vary greatly according to a site's exact location, and its underlying geologic structure. Given that Reno is an area of rapid, active tectonics, with on-going mountain uplift and basin subsidence, the high degree of aleatory variance in the Z values is expected.

Figure 2 together with the curve fits on Figures 3 through 10, do suggest reliable minimum values for the Z1.0 and Z2.5 basin depths across both rock and basin sites in the Reno area. The fits suggest that Z1.0 will be greater than 0.11 km, to 98% confidence. As well, Z2.5 will be greater than 0.25 km, to 98% confidence. These Z minima speak to the depth of weathering effects on the volcanic bedrock in the Reno area. Many measurements show that rock sites generally have a low-velocity surface layer. The most prominent difference between velocities within the Reno-area basin, and outside it on the local bedrock, appears to be simply the thickness of the low-velocity (<760 m/s) surface layer. The low-velocity surface layer is simply thicker in the basins.

Flinchum et al. (2014) made use of this observation in their physics-based computational modeling of ground motions in Las Vegas, Nevada due to the 1992 M5.7 Little Skull Mtn. earthquake. They assembled their 3D community velocity model from southern Nevada Vs30 data in the Louie (2020a) database, plus the 10,722 Vs30 measurements in the Clark County Parcel Map (Pancha et al., 2017a). Flinchum et al. (2014) made regional averages of Vs30 measurements taken in basins, and on rock. Given the averages, where they did not have a measurement, they applied a default rock-site Vs30 of 760 m/s. For basin sites not near a measurement, they applied a default Vs30 of 500 m/s. Similar default Vs30 values could well apply to the Reno area. These default values emphasize the observation that basins and bedrock in Nevada do not have much difference in velocity near the surface.

In Figure 1 there does not appear to be any clear criterion in the Reno area to separate basin from bedrock sites on the basis of their Vs30 value. Weathering and the resulting extreme velocity heterogeneity affect both Vs30 and Z1.0 measurements taken at sites that geologically should be rock sites. The geological location of a measurement, within the basin or on bedrock, does not appear to allow any prediction of Vs30 or Z1.0 in the Reno area. The darker points in Figure 1 come from the Las Vegas basin (Scott et al., 2006), and appear at the end of Table 1. In Las Vegas the gravity analyses of Langenheim et al. (1998; 2001) suggest fast, dense bedrock at depths Zg greater than 0.3 km. These arguably basin locations span the whole range of Vs30 shown in Figure 1 but show apparently "bedrock" Z1.0 values, only as deep as 0.1 km. This phenomenon arises from an abundance of calcified Tertiary soil B horizons, buried throughout western Las Vegas Valley at depths up to 200 m (Scott et al., 2006).

There are a number of measurements of Z1.0 equal to Z2.5 in Table 1 and Figure 2. Many parts of the Reno-area basin are Quaternary in age. Having low-velocity Quaternary sediments directly overlying high-velocity Miocene volcanics, or Mesozoic granites and metavolcanics, is geologically reasonable even at depths approaching 0.5 km (Pancha et al., 2017b). Above those points on the plot having equal Z1.0 and Z2.5, many of the 107 measurements suggest a ratio of Z2.5/Z1.0 of about 2.5. The maximum Z2.5/Z1.0 ratio appears in Figure 2 to be just under 4.0.

Extrapolating Z measurements to unmeasured areas– Given the Louie (2020a) database of shear-wave velocity measurements, we seek a method of extrapolating Z1.0 and Z2.5 to areas without velocity measurements, from other data on basin depths. The Zg values derived from gravity analyses of basin thicknesses are available just about everywhere in Nevada and Eastern California. Reno and Las Vegas have specific analyses that provide much detail on their basin geometries. From the gravity results, it is possible to make general predictions of Z1.0 and Z2.5 depth values anywhere in the region. These predictions may aid the National Seismic Hazard Mapping Project and allow engineers to consider Z1.0 and Z2.5 in assessing earthquake-shaking hazards.

The curve fits on Figures 3 through 10 suggest exponential models to predict Z1.0 and Z2.5 from gravity basin depths Zg. The models are:

$$Z_{1.0}=a_1*\exp(b_1*Z_g),\ a_1=0.1408\ [0.1145,0.1671],\ b_1=0.5484\ [0.2582,0.8387]. \quad \text{(Eq. 1)}$$
$$Z_{2.5}=a_2*\exp(b_2*Z_g),\ a_2=0.3042\ [0.2518,0.3565],\ b_2=0.5478\ [0.3090,0.7867]. \quad \text{(Eq. 2)}$$

The models both had very low R^2 values, 0.09 for the Z1.0 model and 0.15 for the Z2.5 model. The 95% confidence limits on the Z1.0 and Z2.5 predictions are quite wide, reflecting the low correlations. These poor correlations are a result of the extreme, rapid lateral variations in shear-wave velocities at Reno sites. One impact of the resulting poor accuracy in predicting Z1.0 and Z2.5 from Zg is that any seismic-hazard map product using these predictions should not be used to assess the hazard at any specific sensitive site. Instead, specific geological, geophysical, and geotechnical investigations are needed to characterize Z1.0 and Z2.5 properly. However, the poorly predicted Z1.0 and Z2.5 values are accompanied by an uncertainly, between the 95% confidence bounds, that is quite useful. Greater hazard uncertainty implicitly raises hazard levels (Campbell and Bozorgnia, 2013). The predicted Z values and their uncertainties can provide useful regional assessments of hazard, and identify areas where the hazards and their uncertainties are likely to be larger.

The Z2.5 model was applied to the Langenheim et al. (1998, 2001) Zg dataset for Las Vegas. The deepest predicted basin depth using the average coefficients was not deeper than the maximum Zg basin depth of 4.8 km, so the model does not give wholly unacceptable values for basin depth, even at the other end of Nevada from the data in Reno. Z1.0 and Z2.5 were calculated for the Jachens, Abbott, and Langenheim Zg data sets. The percent error between the basin depth calculated from the average coefficients and the depth calculated from the minimizing coefficients get quite high. The modal error for Z1.0 and Z2.5 in the product derived from Abbott and Louie (2000) was 21% and 17% respectively. The maximum errors were 42% and 38% respectively. The maximum errors for the Saltus and Jachens (1995) and the Langenheim et al. (1998, 2001) products are much higher, 100% and 81% respectively.

Figure 11 shows that the Z1.0 model may not apply outside of the Reno basin, since the Z1.0 model consistently overestimated Z1.0 for Las Vegas Valley. These relatively shallow Z1.0 measurements in Las Vegas likely come from buried Neogene soils cemented with caliche (Scott et al., 2006). As a result, Z1.0 is not published for any Zg data outside of the Reno basin. Z2.5 data are published despite there being no direct Z2.5 measurements from Scott et al. (2006) for Las Vegas Valley in the Louie (2020a) seismic shear-wave database.

Data File Format

Assembled measurements of Vs30, Z1.0, and Z2.5 in Reno are given in Table 1. Predicted Z1.0 and Z2.5 results are contained within three plain text data files in the .zip file accompanying this report. Within each text file, Z1.0 and Z2.5 have been estimated for each location listed in the corresponding gravity data set of Zg values: Abbott and Louie (2000) for Reno; Langenheim et al. (1998, 2001) for Las Vegas; and Saltus and Jachens (1995) for the entire Basin and Range. Each location's estimate is one row in the text file.

The columns of the text files, from left to right, are: latitude, degrees WGS84; longitude, degrees WGS84; Zg, km; Z1.0min, km; Z1.0, km; Z1.0max, km; Z2.5min, km; Z2.5, km; Z2.5max, km; Z1.0error, percent; and Z2.5error, percent. The latitude and longitude are converted directly from the published gravity databases, and the Zg values are taken directly from their published results. The Z values are determined as described above from the best-fit coefficients in Equations 1 and 2, estimated from the Zg values. Z values are not forced to any nearby measured Z values that appear in Table 1. The minimum Z values result from the application of the 95% confidence minimum coefficients in Equations 1 and 2; the maximum Z values result from the application of the 95% confidence maximum coefficients in Equations 1 and 2. The Z errors are the percentages resulting from subtracting the minimum Z from the best-fit Z, and then dividing by the best-fit Z.

Users should bear in mind that the Z1.0 estimates are not thought to be valid outside the Reno-area basin. All Z1.0 predictions in the Langenheim and Saltus files, outside the Reno area, should be ignored. Geologically, Z2.5 is thought to coincide with the depth to the floor of Tertiary and Quaternary basins filled with either clastic or volcanic sediments having slower velocity and lesser density, atop denser and faster Mesozoic basement. Figures 12 through 15 present maps of Z1.0 and Z2.5 for Reno, and of Z2.5 for Las Vegas and all of Nevada and Eastern California, respectively. The accompanying .zip file has the map images, as well as a KML file allowing Google Earth to show the Z maps. Map data are supplied also as JRG Packs for plotting and spatial analysis with the free JRG/Viewmat software tools (Louie, 2020b).

Conclusions

The new Louie (2020a) database of ReMi seismic shear-wave velocity soundings (available at https://sites.google.com/view/vs-profile-archive) adds significant data to national earthquake-hazard mapping efforts. It is intended as well for use by geoscience researchers and engineering practitioners in Nevada. Out of hundreds of Vs measurement sites in the database for Nevada and Eastern California, this report examines only those sites in Reno and Las Vegas yielding both Vs30 and Z1.0 measurements. There are 170 such sites in Reno and 49 in Las Vegas, with 107 of them also having a Z2.5 measurement. Table 1 summarizes the location, Vs30, Z1.0, and Z2.5 measurements, along with gravity-derived Zg estimates for the 219 sites. Most of these data have been previously published.

Examination of the Vs30 measurements at the 219 sites reveals the following characteristics:

- All but a few sites have Vs30 between 260 m/s and 760 m/s.
- A majority of the sites have Vs30 measurements in NEHRP hazard class C.
- Sites that are geologically on bedrock have unexpectedly low Vs30, with almost all considerably lower than 760 m/s.
- Bedrock sites investigated with intensive surveying programs (e.g., Pancha et al., 2008) show extreme lateral variability of Vs30, with velocity variations of greater than 20% observed over distances of tens of meters.

- There appear to be no geological- or soil-mapping criteria able to predict Vs30 in Nevada, as discovered by Scott et al. (2004) for Reno, by Scott et al. (2006) and Pancha et al. (2017a) for Las Vegas.
- Vs30 does not distinguish basin from bedrock sites in Nevada. Basin sites may well have faster Vs30 measurements than nearby bedrock sites.

Measurements of Z1.0 and Z2.5 at these 219 Nevada sites reveal the following characteristics:

- Some bedrock sites have Z1.0 measurements exceeding 0.1 km.
- Some basin sites have Z1.0 measurements of less than 0.05 km.
- It is not possible to definitively separate geologically defined basin sites from bedrock sites on the basis of their measured Z1.0 depth.
- Bedrock sites investigated with intensive surveying programs (e.g., Pancha et al., 2008) show extreme lateral variability of Z depths, with great variations observed over distances of tens of meters.
- In the Reno area, measured Z1.0 varies from 0.015 km to 0.45 km; Z2.5 varies from 0.1 km to 0.9 km.
- Reno-area basin Z2.5 measurements vary according to geologic structure.
- Reno-area bedrock Z measurements vary greatly over short distances due to differential weathering of volcanic rocks.
- In 49 Las Vegas measurements along Las Vegas Blvd., Z1.0 varies from 0.05 to 0.68 km; Z2.5 measurements are not available.
- In the 49 Las Vegas measurements, Z1.0 is typically between 0.05 km and 0.11 km. Variations are likely due to highly variable occurrence of Tertiary caliche cementation.
- In the Reno area, the ratio of Z2.5 over Z1.0 measurements at a site is established with a minimum of 1.0, and with some sites exhibiting a ratio as high as 4.5.

We undertook an effort to produce Z1.0 and Z2.5 maps predicting Z depths across Nevada and Eastern California. We were able to determine models to predict Z1.0 and Z2.5 from gravity-derived thicknesses Zg with some constraints on uncertainties at 95% confidence. The percent errors are lower in Reno, higher in Las Vegas, and much higher in the Saltus and Jachens (1995) dataset, but still reasonable. Correlation coefficients are very poor, suggesting that the predicted Z maps not be used at individual sites, but only for broad regional assessments.

The models were determined by fitting the seismic data in Reno, Nevada, where the maximum measured Z2.5 is 1.2 km. It is a leap to apply them to Las Vegas data with Zg values as deep as 4.8 km, and an even bigger leap to apply it to the Saltus and Jachens (1995) dataset that spans much of the Great Basin down to the Arizona-Mexico border, with many calderas and Neogene basins having Zg exceeding 8 km. Still, the uncertainties accompanying the Z predictions will be useful in hazard studies.

These estimated Z maps may still prove a useful tool in seismic hazard studies, by pinpointing areas of interest for further measurements. More seismic surveys to determine Z1.0 and Z2.5 are needed in the future to provide additional constraints, and to refine these models. Efforts are underway to measure additional Z2.5 depths in Reno, and to integrate the geophysical and geological views of the basin. Given the current 2.3 million population of Las Vegas, and the city’s economic importance to the State of Nevada, immediate efforts should begin to measure Z2.5 throughout the basin.

<u>Declaration of Potential Perceived Conflict of Interest</u>

The ReMi technology is owned by the University of Nevada, and licensed exclusively to Optim Earth, Inc. Optim pays royalties to the University based on their commercial revenues from ReMi. As inventor of the technology, under University policy John Louie personally receives a share of those royalties.

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Disclaimers

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Any measurements and observations made within approximately 50 km of Yucca Mountain, Nevada, and specifically any locations or magnitudes of seismic events, are preliminary information only. Please contact the archive of the Yucca Mountain Project Technical Library to obtain quality-assured technical data relating to seismic activity, ground conditions, or other natural phenomena near Yucca Mountain.

The information included in these documents is intended to improve earthquake preparedness; however, it does not guarantee the safety of an individual structure or facility. The State of Nevada does not assume liability for any injury, death, or property damage that occurs in connection with an earthquake.

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Figures

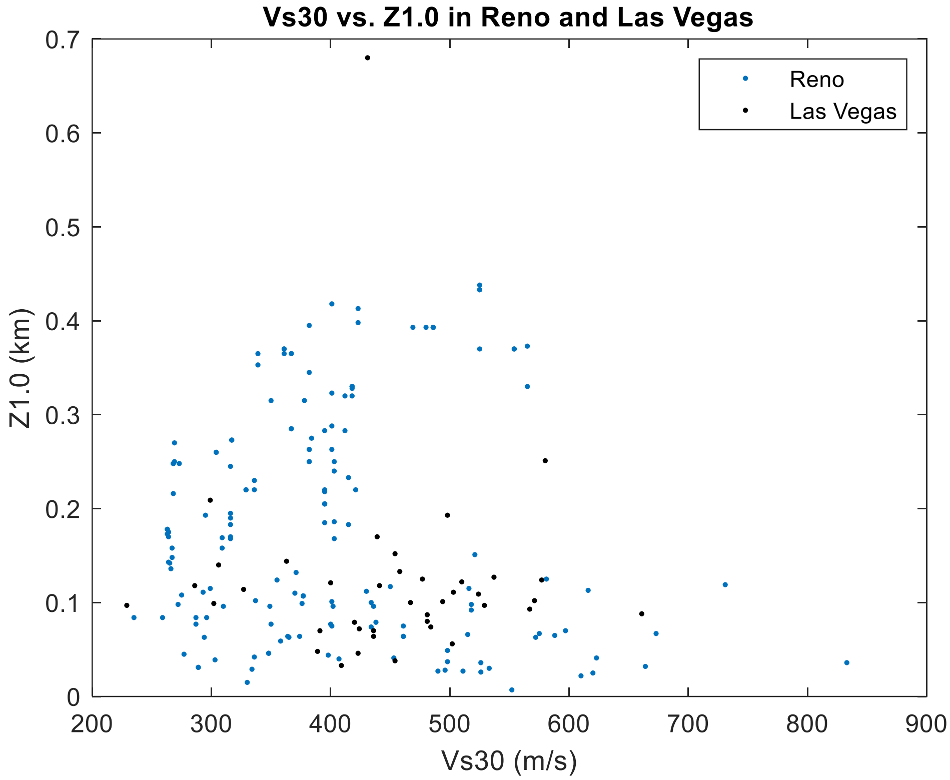

Figure 1: Graph of Z1.0 vs. Vs30 from Reno and Las Vegas seismic shear-wave data.

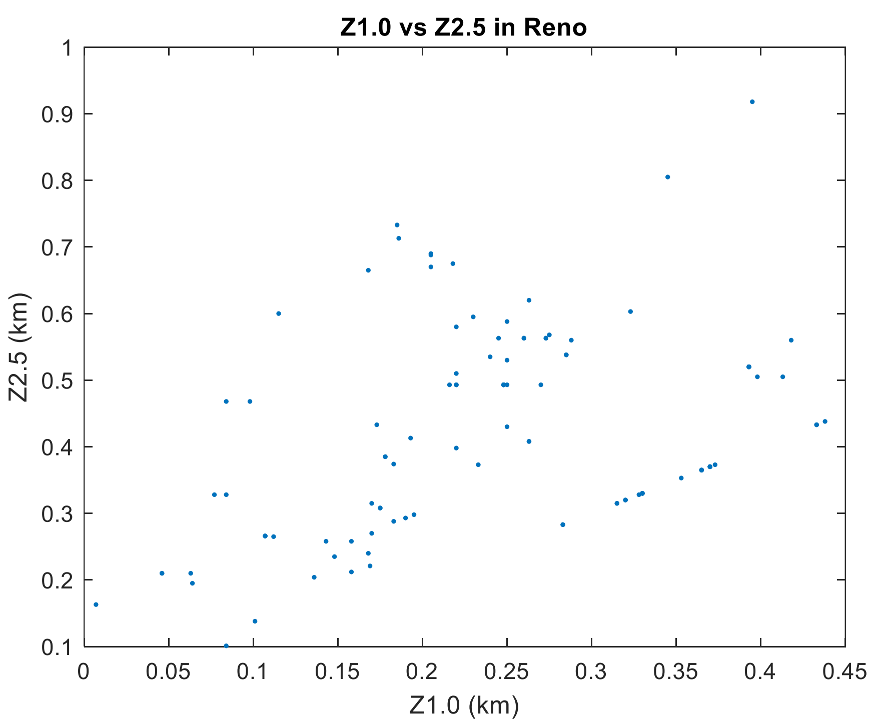

Figure 2: Graph of Z2.5 vs. Z1.0 from Reno seismic shear-wave data.

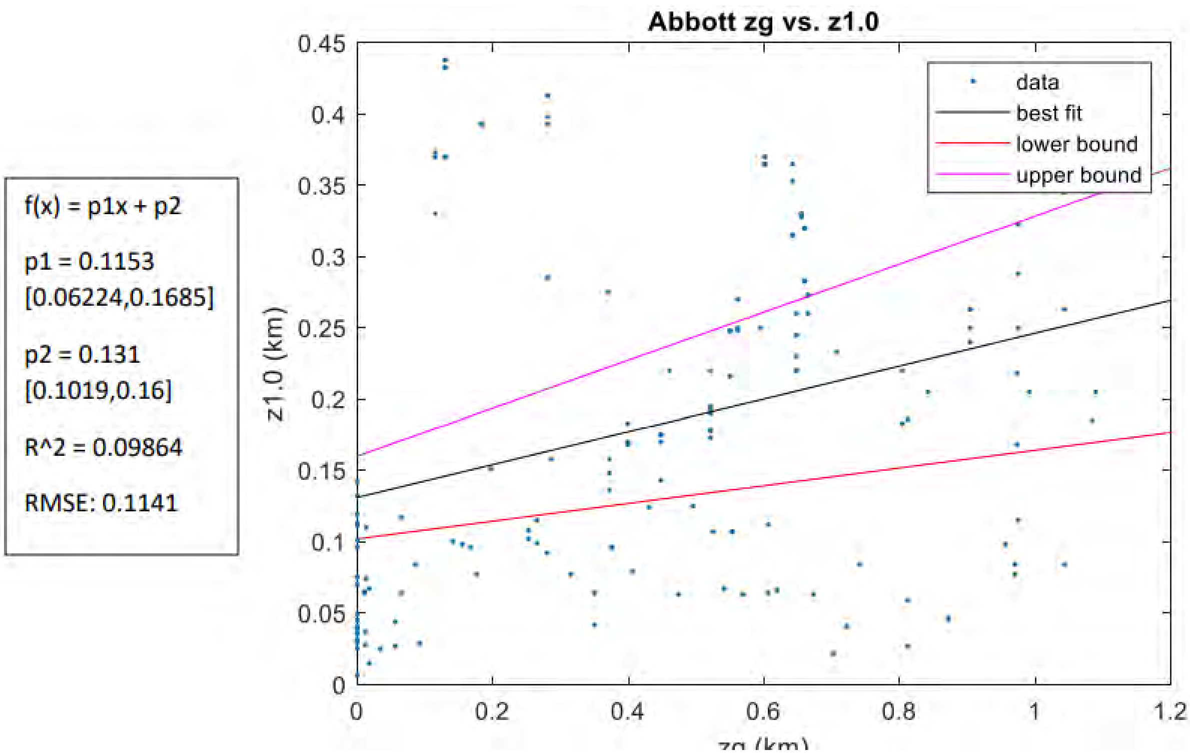

Figure 3: Linear model of Z1.0 vs. Zg in Reno

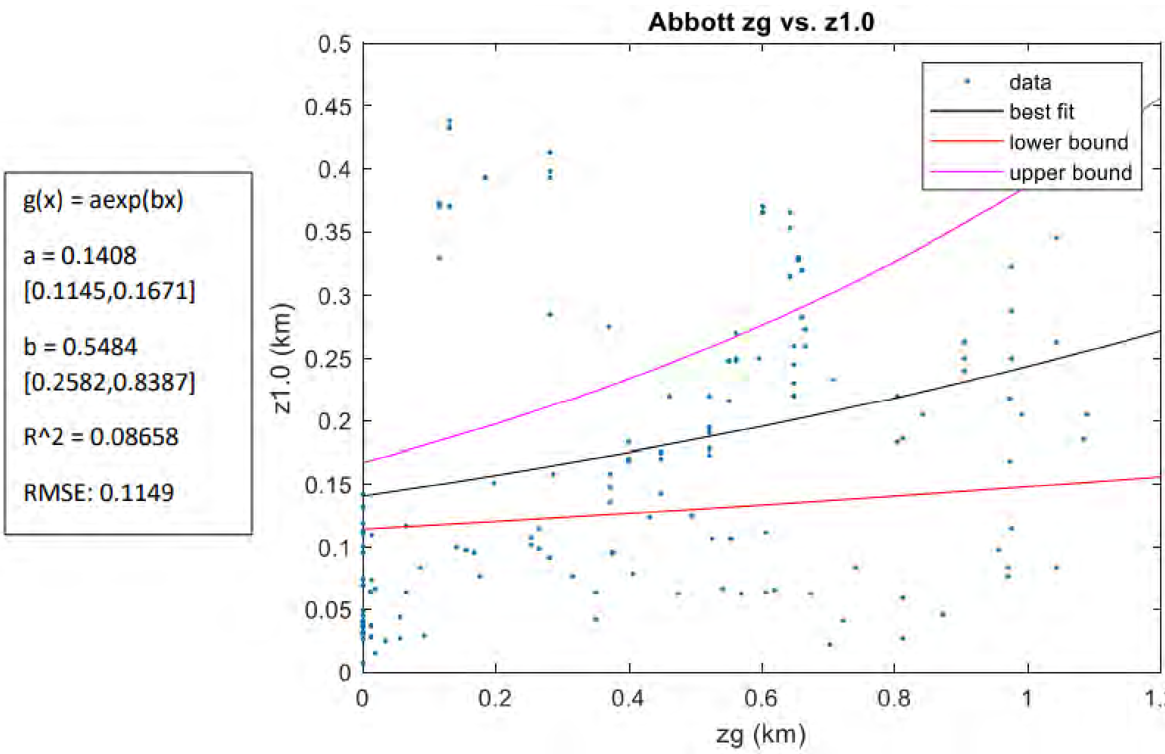

Figure 4: Exponential model of Z1.0 vs. Zg in Reno

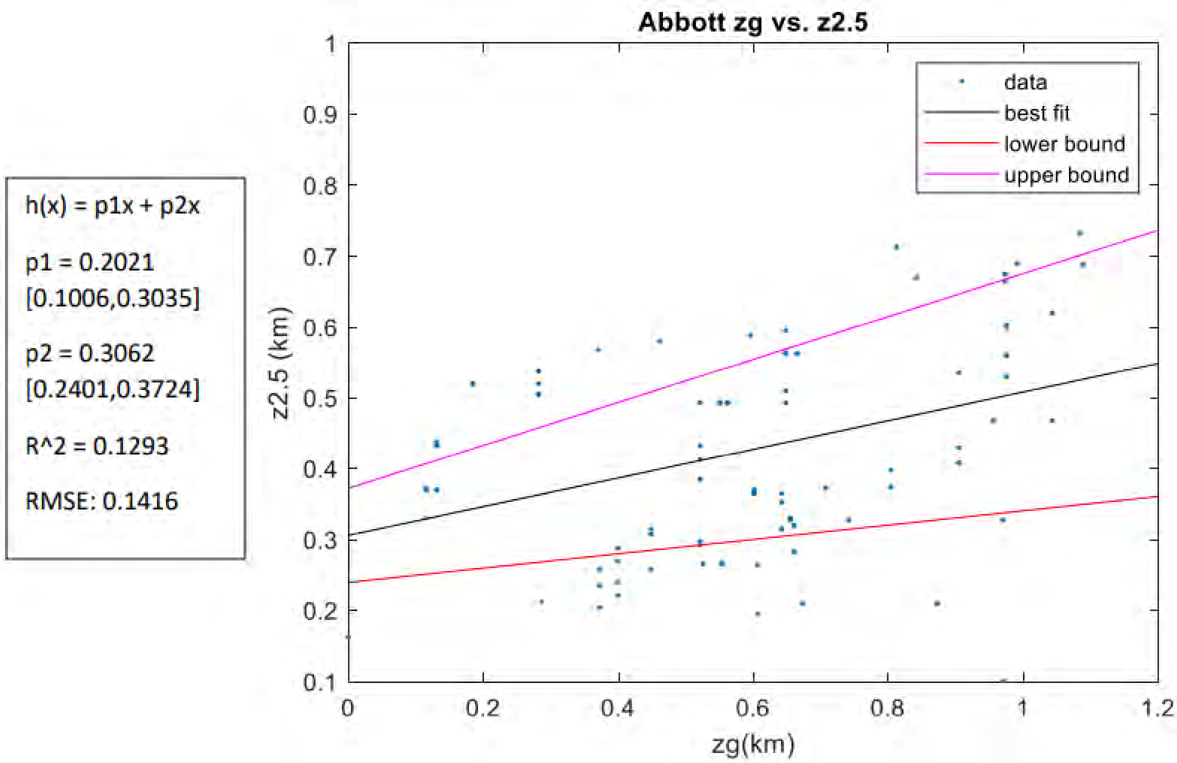

Figure 5: Linear model of Z2.5 vs. Zg in Reno

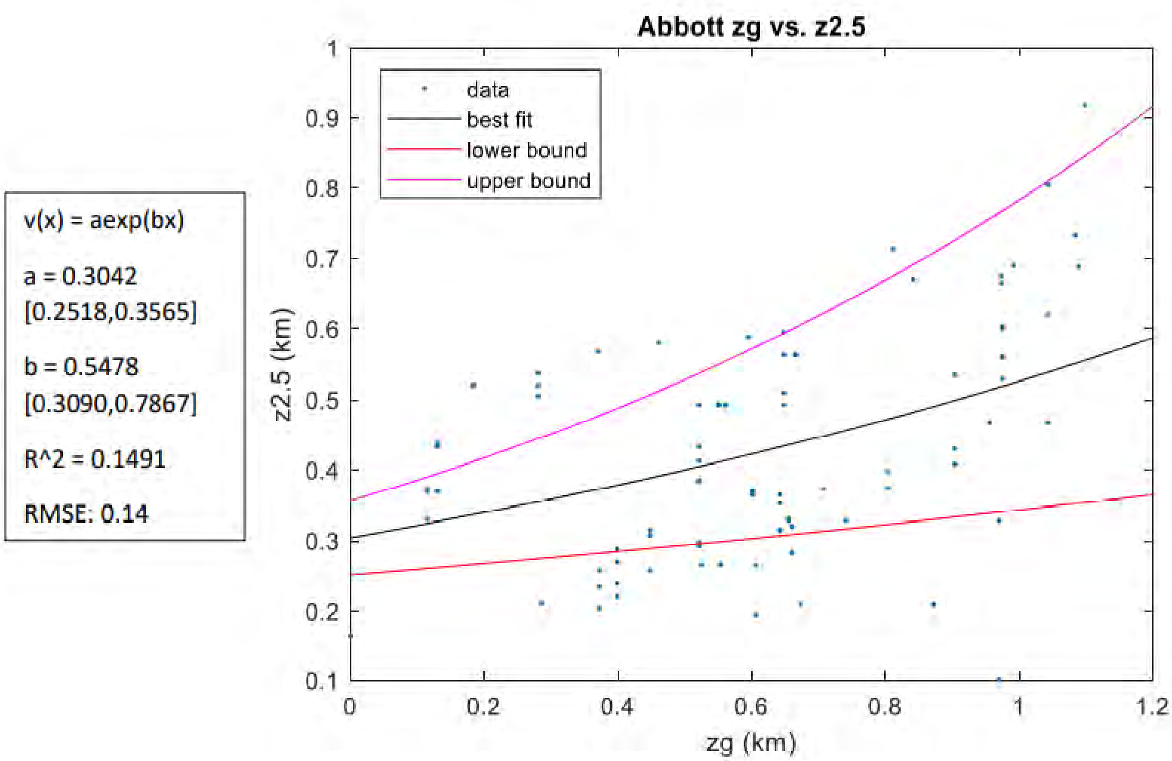

Figure 6: Exponential model of Z2.5 vs. Zg in Reno

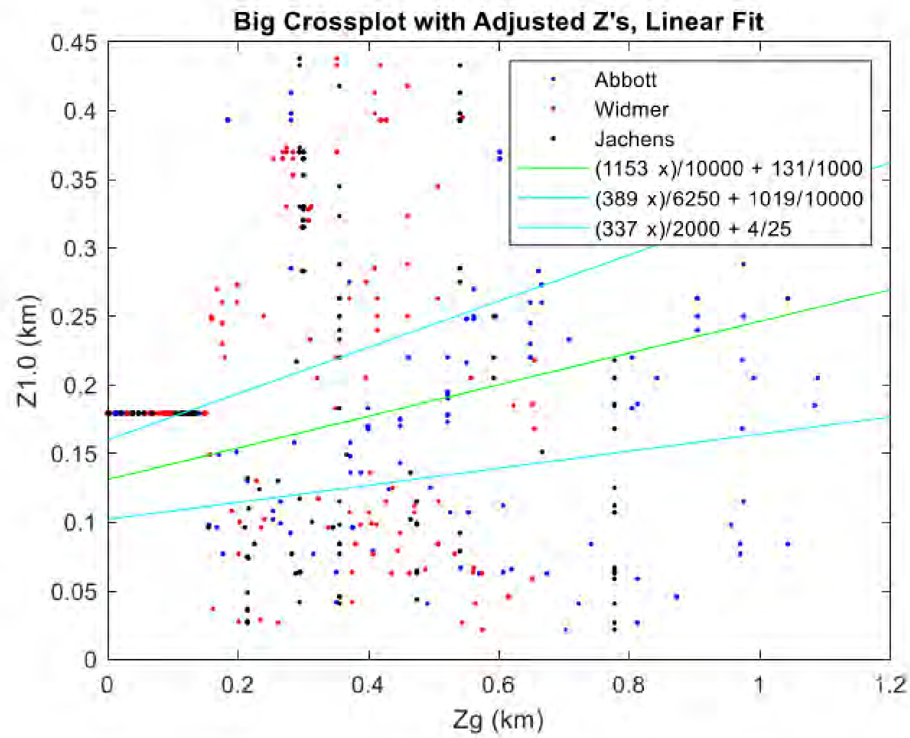

Figure 7: All Reno shear-wave data plotted against all Reno gravity data. Linear model of Z1.0.

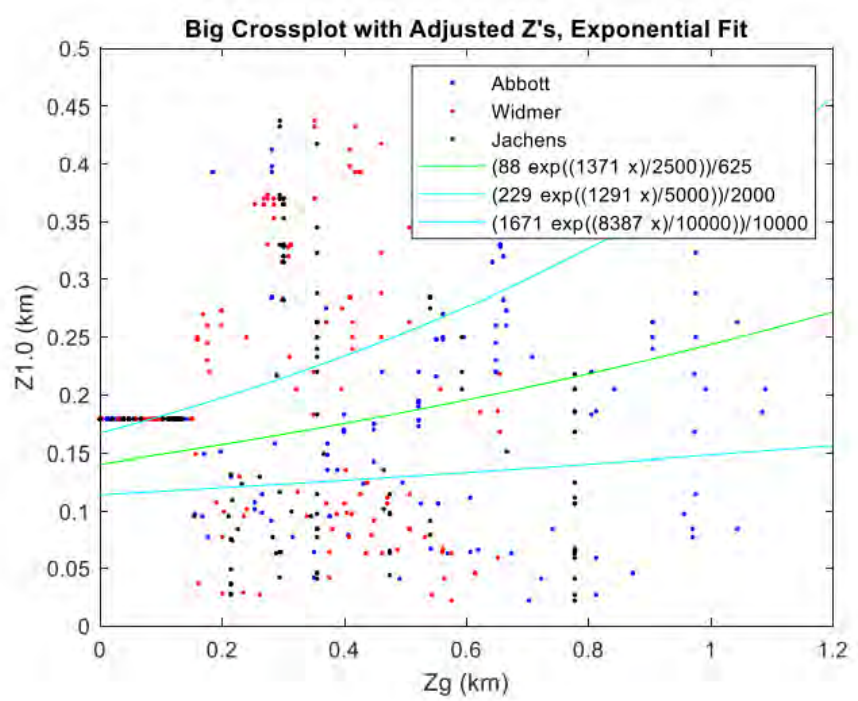

Figure 8: All Reno shear-wave data plotted against all Reno gravity data. Exponential model of Z1.0.

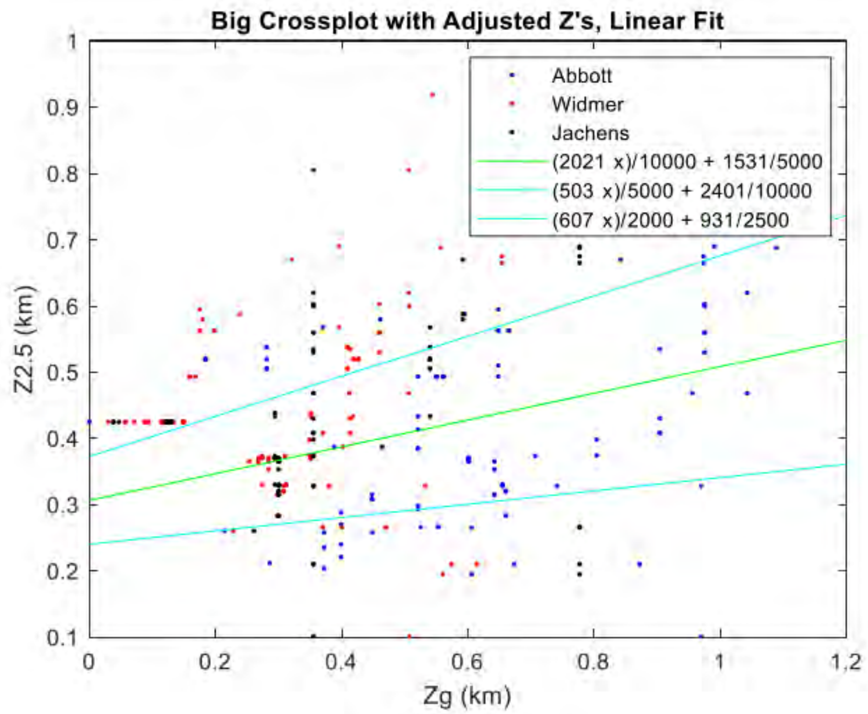

Figure 9: All Reno shear-wave data plotted against all Reno gravity data. Linear model of Z2.5.

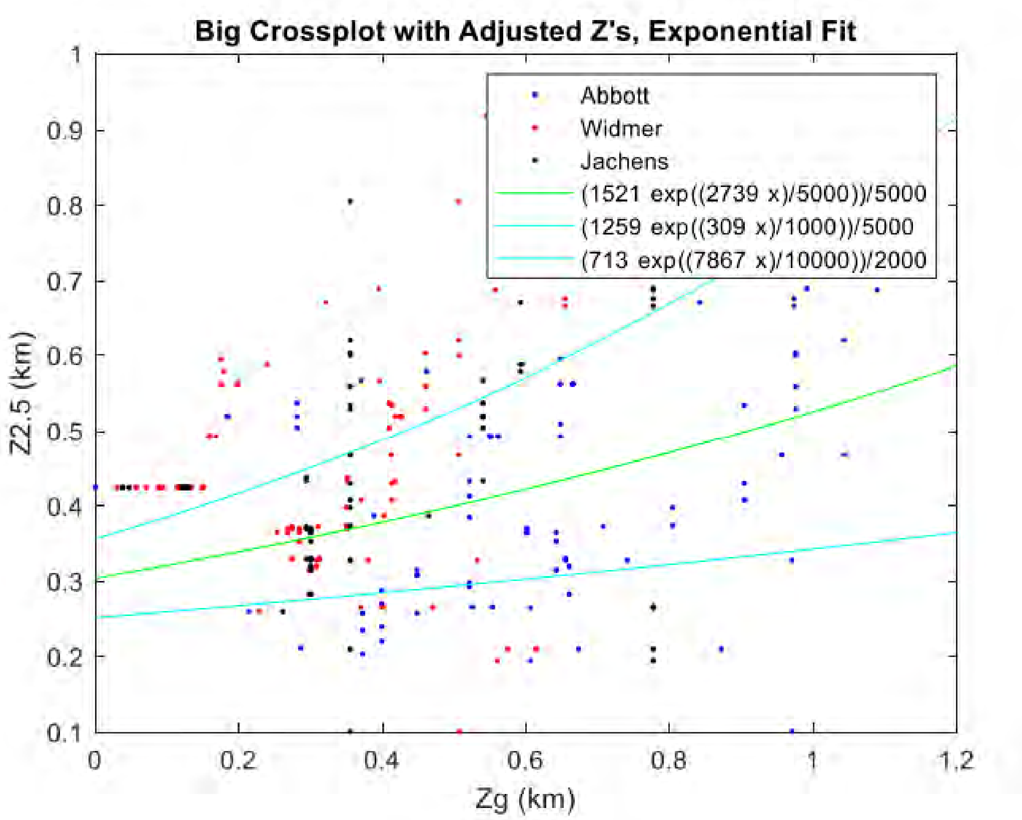

Figure 10: All Reno shear-wave data plotted against all Reno gravity data. Exponential model of Z2.5.

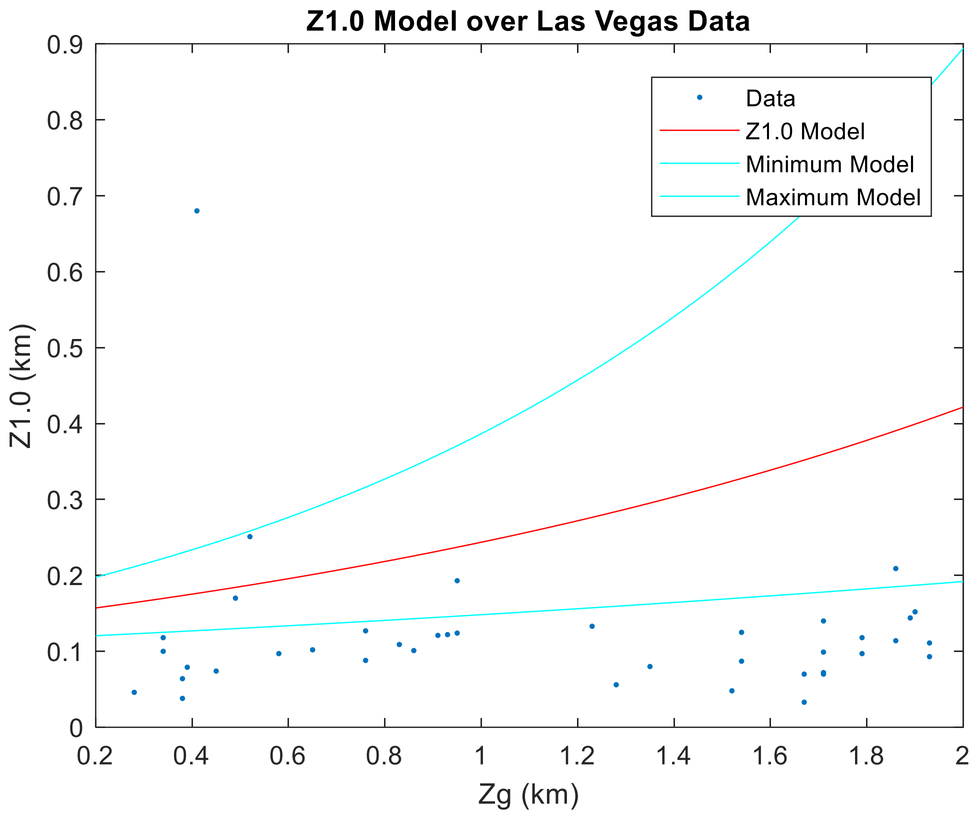

Figure 11: Z1.0 model applied to Las Vegas Shear-Wave Velocity Basin-Depth Data

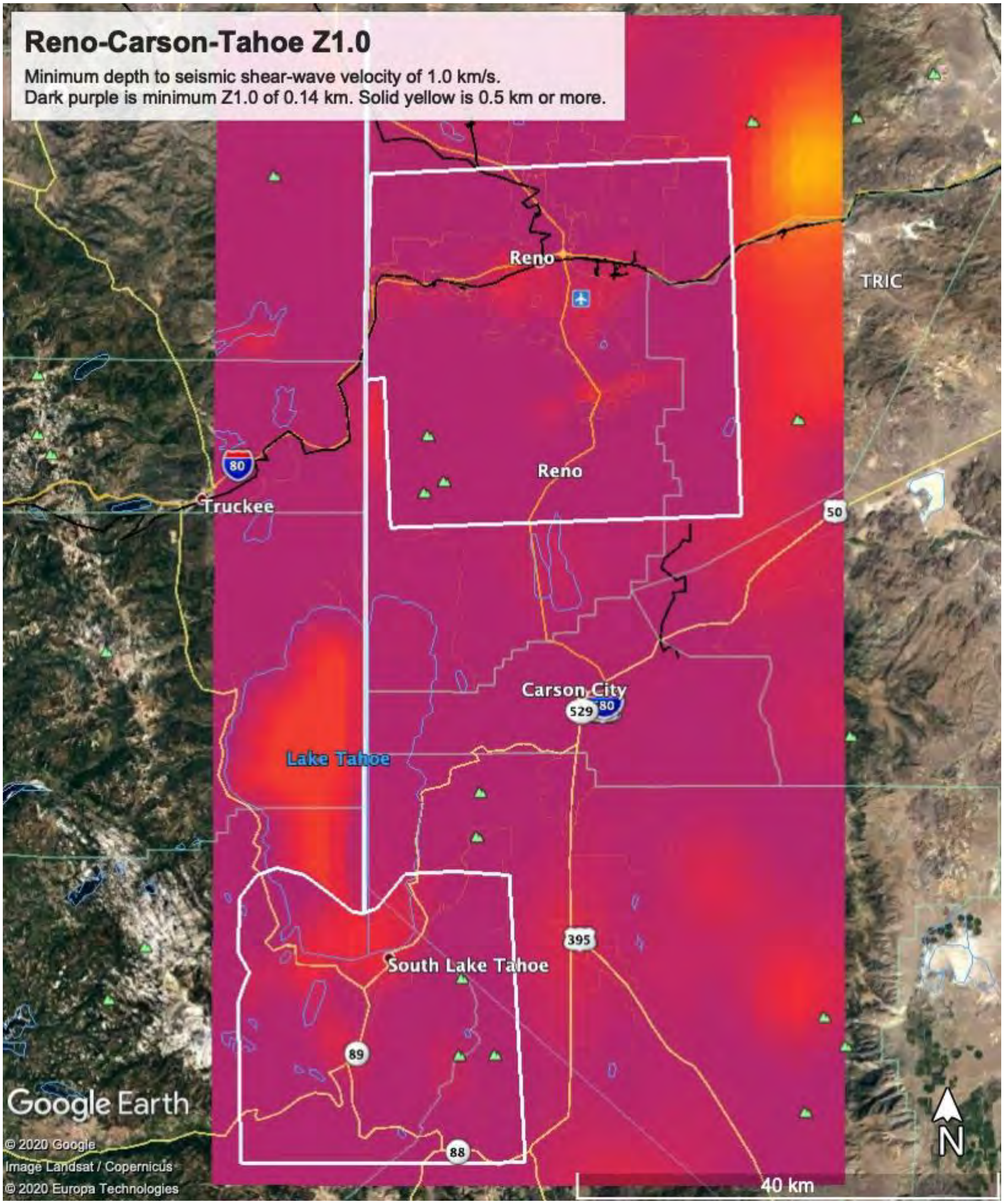

Figure 12: Z1.0 map for the Reno area. Z1.0 values estimated with Eq. 1 from Abbott and Louie (2000) Zg values are within the white-outlined area around Reno. Louie et al. (2016) provide Zg values as well as shear-velocity data in the South Lake Tahoe area, but we have not examined Z cross-plots for that region. Saltus and Jachens (1995) provide the remaining Zg values east of the vertical white line, which is the Nevada border at -120° longitude. West of -120°, basin thicknesses are guessed from bedrock proximity. The shape of the basin underlying the northwest part of Lake Tahoe is particularly uncertain.

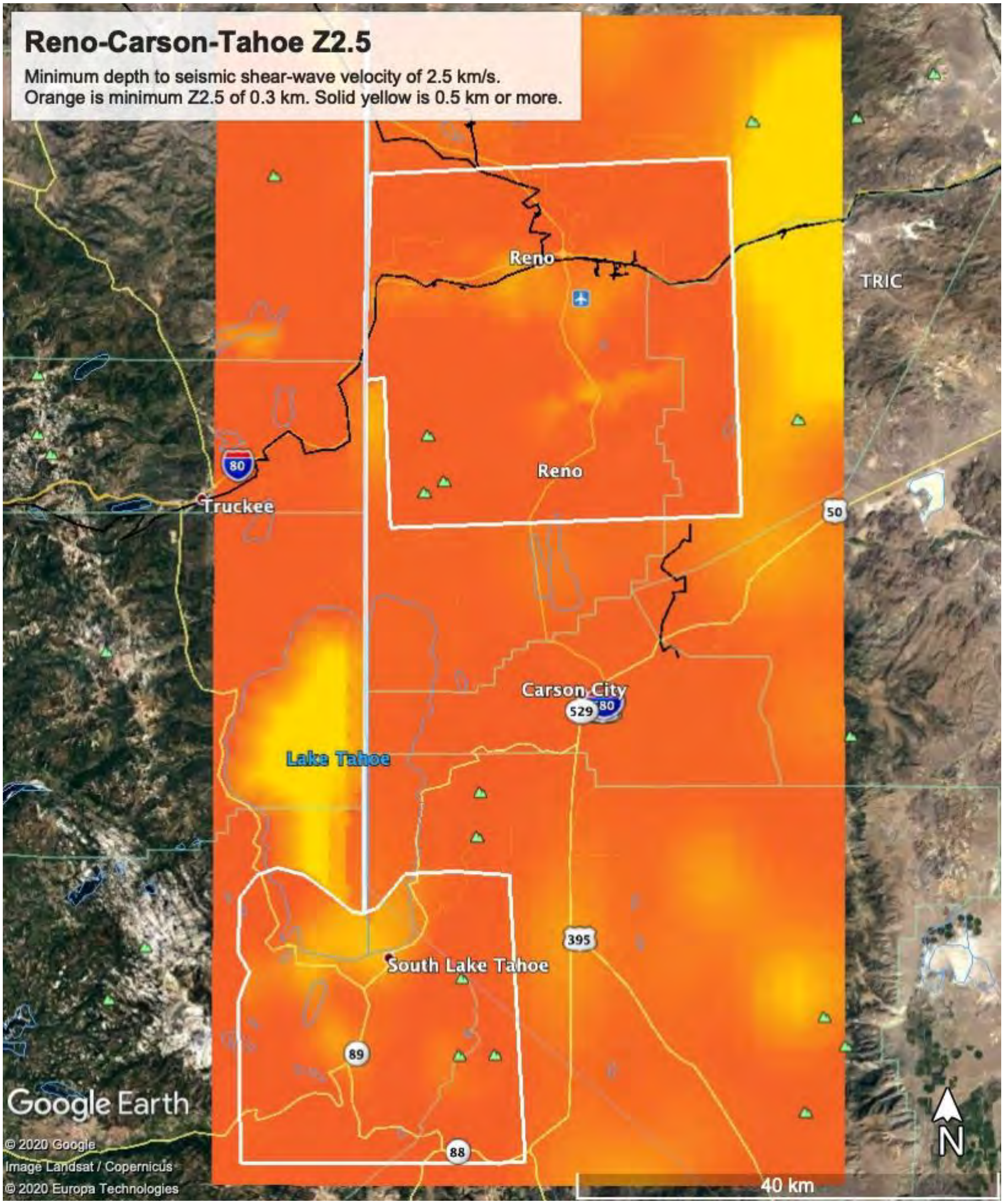

Figure 13: Z2.5 map for the Reno area. Z2.5 values estimated with Eq. 2 from Abbott and Louie (2000) Zg values are within the white-outlined area around Reno. Louie et al. (2016) provide Zg values as well as shear-velocity data in the South Lake Tahoe area, but we have not examined Z cross-plots for that region. Saltus and Jachens (1995) provide the remaining Zg values east of the vertical white line, which is the Nevada border at -120° longitude. West of -120°, basin thicknesses are guessed from bedrock proximity. The shape of the basin underlying the northwest part of Lake Tahoe is particularly uncertain.

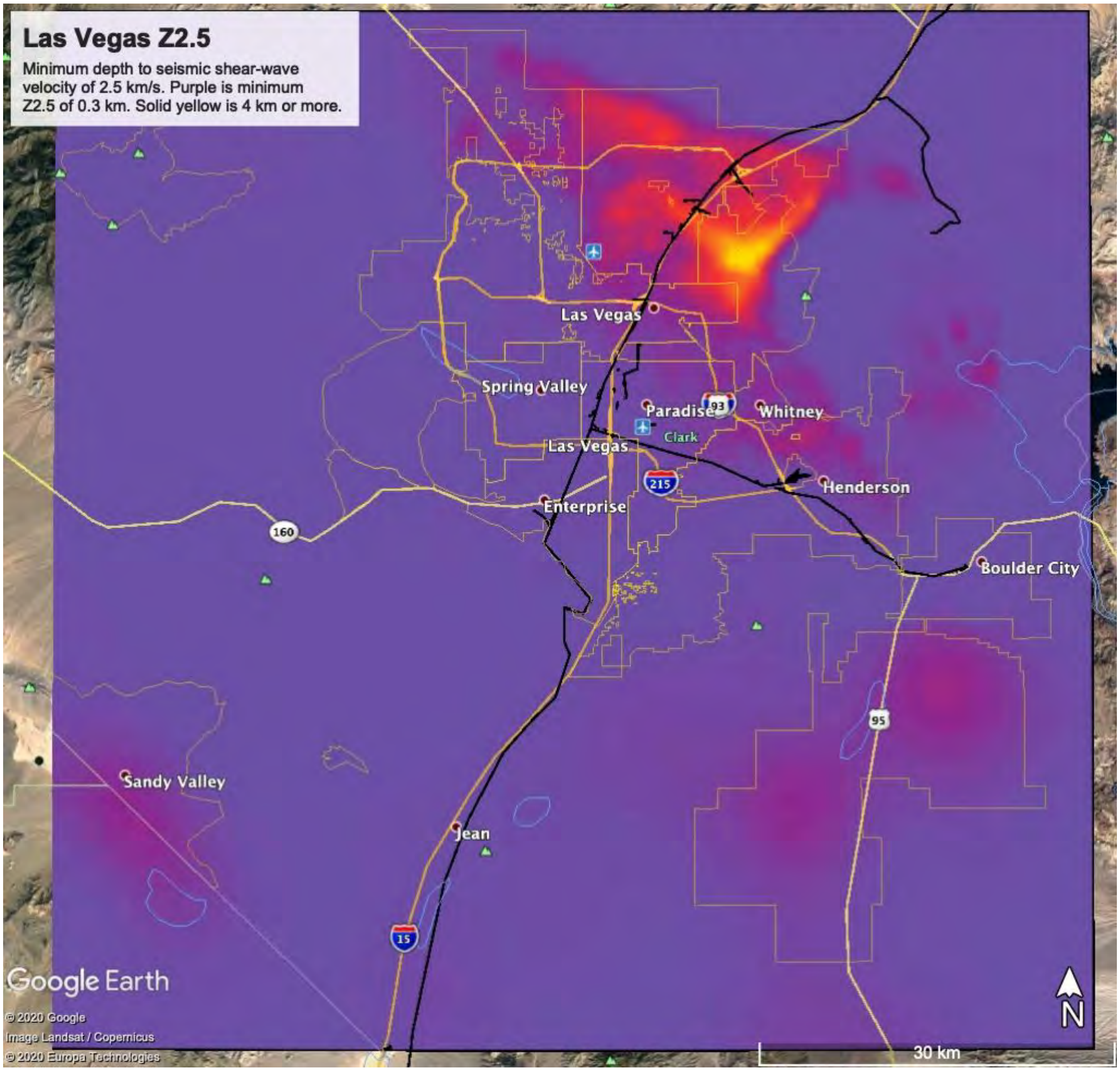

Figure 14: Z2.5 map for the Las Vegas area. Z2.5 values are estimated with Eq. 2 from Langenheim et al. (1998; 2001) Zg values in the northern half of the map. Saltus and Jachens (1995) provide the remaining Zg values.

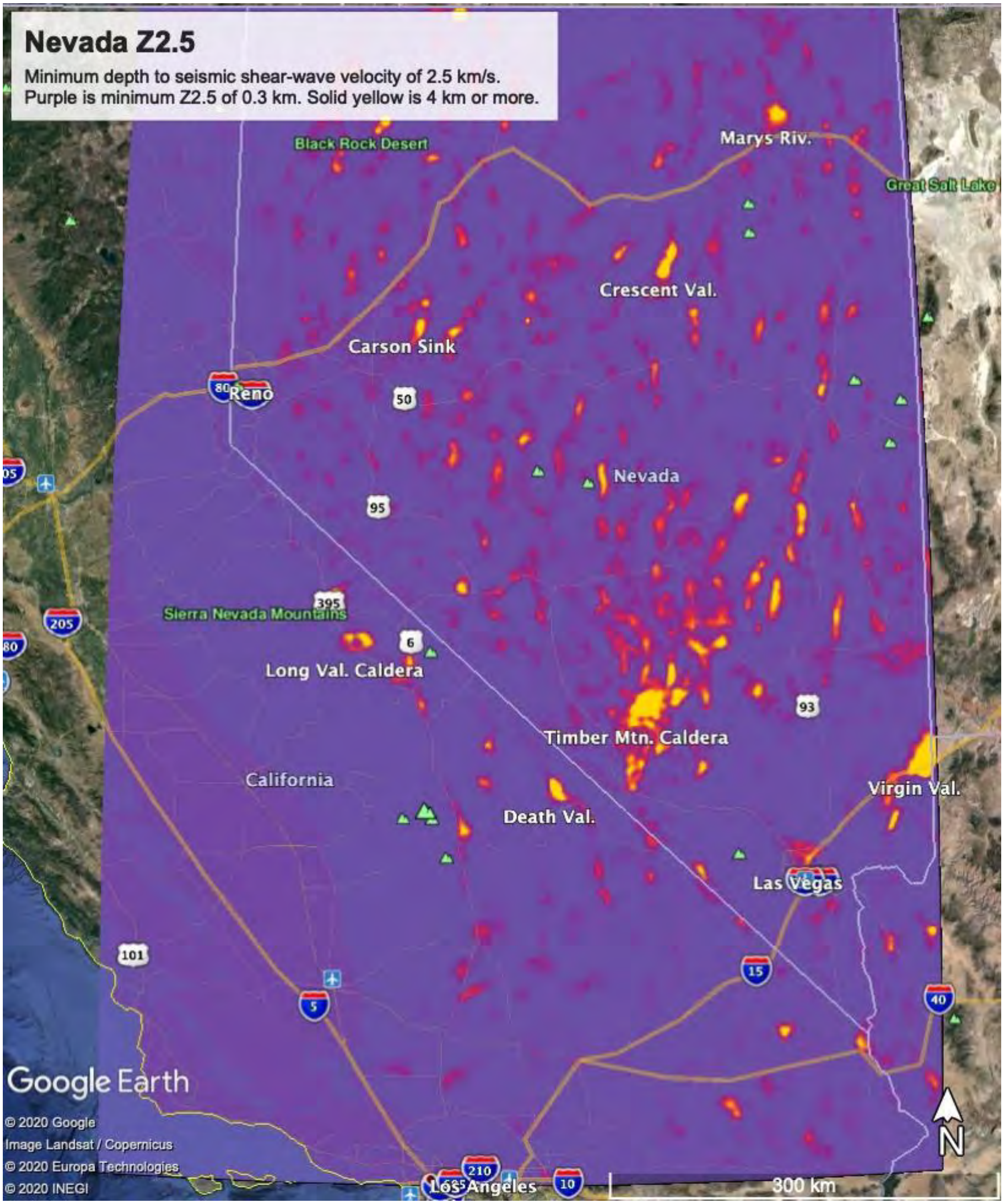

Figure 15: Z2.5 map for Nevada and Eastern California. Z2.5 values are estimated with Eq. 2 from Saltus and Jachens (1995) Zg values. Prominently deep sedimentary and volcanic basins are labeled. The Saltus and Jachens (1995) Zg values are valid only east of -120° longitude and east of the Sierra Nevada crest. This analysis does not constrain Z2.5 values to the west.

Table 1: Selected Shear Velocity Measurements from Reno and Las Vegas
Latitudes and Longitudes are in degrees and WGS84 datum. File names from Louie (2020a) archive.

File Name	Latitude	Longitude	Vs30 (m/s)	Z1.0 (km)	Z2.5 (km)	Zg (km)
1002-087.txt	39.5206	-119.808	461	0.064	>0.165	0.065
1002-354.txt	39.5275	-119.802	498	0.049	>0.059	0
1003-087.txt	39.5044	-119.808	461	0.064	>0.165	0.35
1004-087.txt	39.5045	-119.806	336	0.042	>0.200	0.35
1009-355.txt	39.5247	-119.806	511	0.027	>0.032	0.056
101-115-284.txt	39.51663	-119.705	616	0.113	>0.460	0
1010-355.txt	39.52463	-119.803	496	0.028	>0.032	0.012
1011-355.txt	39.5265	-119.803	498	0.037	>0.044	0.012
1016-355.txt	39.52732	-119.801	526	0.036	>0.115	0
116-130-284.txt	39.51478	-119.707	673	0.067	>0.340	0.018
131-145-284.txt	39.51321	-119.71	330	0.015	>0.340	0.018
161-175-288.txt	39.5127	-119.717	334	0.029	>0.275	0.092
236-250-288.txt	39.51137	-119.734	349	0.096	>0.440	0.375
356-364-289.txt	39.51523	-119.759	402	0.096	>0.220	0.376
416-430-353.txt	39.52204	-119.77	434	0.1	>0.270	0.141
646-660-312.txt	39.53055	-119.791	401	0.075	>0.330	0
661-675-312.txt	39.52984	-119.794	461	0.075	>0.230	0
691-705-313.txt	39.52942	-119.801	371	0.132	>0.215	0
766-775-313.txt	39.52438	-119.815	518	0.098	>0.265	0.155
776-790-319.txt	39.52433	-119.817	516	0.115	>0.340	0.265
791-805-319.txt	39.52259	-119.82	518	0.092	>0.320	0.28
836-850-319.txt	39.51998	-119.828	438	0.079	>0.300	0.406
851-865-319.txt	39.51982	-119.832	572	0.063	>0.310	0.474
881-895-340.txt	39.51918	-119.838	575	0.067	>0.330	0.541
896-910-340.txt	39.51764	-119.84	515	0.066	>0.325	0.619
911-925-340.txt	39.51635	-119.843	453	0.041	>0.320	0.722
926-940-340.txt	39.51499	-119.846	610	0.022	>0.425	0.702
941-955-340.txt	39.51231	-119.847	490	0.027	>0.330	0.812
956-970-353.txt	39.51101	-119.85	358	0.059	>0.350	0.812
BMHS.txt	39.4245	-119.765	400	0.077	>0.200	0.315
CCAD-PO-RS.txt	39.16403	-119.779	289	0.031	>0.131	0
CCAD-RS.txt	39.16403	-119.779	289	0.031	>0.131	0
CCAD-SDS-RS.txt	39.16403	-119.779	293	0.111	>0.152	0
CF02-RS.txt	39.1904	-119.742	277	0.045	>0.100	0
demo-UNRQuad.txt	39.53827	-119.814	398	0.044	>0.100	0.056
EagleValleyMiddleSchool-s2-remi.txt	39.15809	-119.722	310	0.096	>0.196	0
egge1-10.txt	39.53871	-119.815	588	0.065	>0.100	0.011
EGLV-RS.txt	39.15903	-119.719	303	0.039	>0.080	0
EVAN.txt	39.53915	-119.812	364	0.064	>0.164	0.011
fLine1_01_to_30_mod.txt	39.5276	-119.746	367	0.365	0.365	0.601

File Name	Latitude	Longitude	Vs30 (m/s)	Z1.0 (km)	Z2.5 (km)	Zg (km)
fLine1_03_to_32_mod.txt	39.5276	-119.745	361	0.365	0.365	0.601
fLine1_11_to_40_mod.txt	39.5276	-119.74	339	0.353	0.353	0.642
fLine1_13_to_42_mod.txt	39.5275	-119.739	350	0.315	0.315	0.642
fLine1_15_to_44_mod.txt	39.5275	-119.738	378	0.315	0.315	0.642
fLine1_17_to_46_mod.txt	39.5275	-119.737	395	0.283	0.283	0.66
fLine1_19_to_48_mod.txt	39.5274	-119.736	412	0.283	0.283	0.66
fLine1_21_to_50_mod.txt	39.5274	-119.735	418	0.32	0.32	0.66
fLine1_23_to_52_mod.txt	39.5273	-119.733	412	0.32	0.32	0.66
fLine1_25_to_54_mod.txt	39.5273	-119.732	418	0.328	0.328	0.655
fLine1_27_to_56_mod.txt	39.5274	-119.731	418	0.33	0.33	0.655
fLine1_29_to_58_mod.txt	39.5274	-119.73	418	0.33	0.33	0.655
fLine1_31_to_60_mod.txt	39.5274	-119.729	418	0.33	0.33	0.655
fLine2_01_to_30_mod.txt	39.5127	-119.82	384	0.275	0.568	0.37
fLine2_04_to_33_mod.txt	39.5127	-119.819	367	0.285	0.538	0.281
fLine2_22_to_51_mod.txt	39.5125	-119.808	525	0.438	0.438	0.13
fLine2_31_to_60_mod.txt	39.5129	-119.803	565	0.33	0.33	0.115
HVGC-RS.txt	39.49113	-11.7208	265	0.142	>0.150	0
Line1_01_to_30_mod.txt	39.5349	-119.715	317	0.273	0.563	0.665
Line1_02_to_31_mod.txt	39.5276	-119.746	367	0.365	0.365	0.601
Line1_03_to_32_mod.txt	39.5359	-119.715	317	0.273	0.563	0.665
Line1_04_to_33_mod.txt	39.5364	-119.715	304	0.26	0.563	0.665
Line1_05_to_34_mod.txt	39.5276	-119.744	361	0.37	0.37	0.601
Line1_06_to_35_mod.txt	39.5373	-119.715	304	0.26	0.563	0.648
Line1_07_to_36_mod.txt	39.5276	-119.743	361	0.37	0.37	0.601
Line1_08_to_37_mod.txt	39.5382	-119.715	316	0.245	0.563	0.648
Line1_09_to_38_mod.txt	39.5276	-119.742	339	0.365	0.365	0.642
Line1_10_to_24_mod.txt	39.504	-119.848	365	0.063	0.21	0.673
Line1_10_to_39_mod.txt	39.5391	-119.715	336	0.23	0.595	0.648
Line1_11_to_25_mod.txt	39.5047	-119.846	374	0.064	0.195	0.606
Line1_11_to_40_mod.txt	39.5395	-119.715	336	0.22	0.51	0.648
Line1_12_to_26_mod.txt	39.5049	-119.844	430	0.112	0.265	0.606
Line1_13_to_27_mod.txt	39.5049	-119.842	377	0.107	0.266	0.553
Line1_13_to_42_mod.txt	39.5404	-119.715	329	0.22	0.493	0.648
Line1_14_to_28_mod.txt	39.5051	-119.839	377	0.107	0.266	0.553
Line1_15_to_44_mod.txt	39.5413	-119.715	329	0.22	0.493	0.521
Line1_16_to_30_mod.txt	39.5049	-119.835	377	0.107	0.266	0.525
Line1_17_to_46_mod.txt	39.5424	-119.715	295	0.193	0.413	0.521
Line1_19_to_48_mod.txt	39.5432	-119.715	316	0.195	0.298	0.521
Line1_1_to_15_mod.txt	39.5008	-119.871	287	0.084	0.328	0.741
Line1_21_to_50_mod.txt	39.5441	-119.715	316	0.19	0.293	0.521
Line1_23_to_52_mod.txt	39.545	-119.715	316	0.183	0.288	0.399
Line1_25_to_54_mod.txt	39.5459	-119.715	316	0.17	0.27	0.399

File Name	Latitude	Longitude	Vs30 (m/s)	Z1.0 (km)	Z2.5 (km)	Zg (km)
Line1_27_to_56_mod.txt	39.5468	-119.715	316	0.168	0.24	0.399
Line1_29_to_58_mod.txt	39.5477	-119.715	309	0.169	0.221	0.399
Line1_2_to_16_mod.txt	39.5014	-119.867	272	0.098	0.468	0.956
Line1_31_to_60_mod.txt	39.5486	-119.715	309	0.158	0.212	0.286
Line1_3_to_17_mod.txt	39.5016	-119.865	259	0.084	0.468	1.043
Line1_4_to_18_mod.txt	39.5013	-119.861	299	0.115	0.6	0.975
Line1_5_to_19_mod.txt	39.5008	-119.859	235	0.084	0.101	0.97
Line1_6_to_20_mod.txt	39.5011	-119.857	287	0.077	0.328	0.97
Line1_7_to_21_mod.txt	39.5019	-119.855	348	0.046	0.21	0.872
Line1_8_to_22_mod.txt	39.5024	-119.853	348	0.046	0.21	0.872
Line2_01_to_30_mod.txt	39.5418	-119.722	269	0.27	0.493	0.561
Line2_02_to_31_mod.txt	39.5418	-119.721	269	0.25	0.493	0.561
Line2_03_to_32_mod.txt	39.5127	-119.819	367	0.285	0.538	0.281
Line2_04_to_33_mod.txt	39.5419	-119.72	273	0.248	0.493	0.561
Line2_05_to_34_mod.txt	39.5127	-119.818	423	0.398	0.505	0.281
Line2_06_to_35_mod.txt	39.5419	-119.719	268	0.248	0.493	0.55
Line2_07_to_36_mod.txt	39.5128	-119.817	423	0.413	0.505	0.281
Line2_08_to_37_mod.txt	39.5418	-119.718	268	0.248	0.493	0.55
Line2_09_to_38_mod.txt	39.5129	-119.816	469	0.393	0.52	0.281
Line2_10_to_24_mod.txt	39.4978	-119.863	403	0.24	0.535	0.904
Line2_10_to_39_mod.txt	39.5418	-119.716	268	0.248	0.493	0.55
Line2_11_to_25_mod.txt	39.4971	-119.863	382	0.25	0.43	0.904
Line2_11_to_40_mod.txt	39.5129	-119.815	480	0.393	0.52	0.184
Line2_12_to_26_mod.txt	39.4965	-119.864	382	0.263	0.408	0.904
Line2_12_to_41_mod.txt	39.5418	-119.715	268	0.216	0.493	0.55
Line2_13_to_27_mod.txt	39.496	-119.865	382	0.263	0.408	0.904
Line2_13_to_42_mod.txt	39.5129	-119.813	486	0.393	0.52	0.184
Line2_14_to_28_mod.txt	39.4952	-119.865	421	0.22	0.398	0.804
Line2_14_to_43_mod.txt	39.5418	-119.714	263	0.173	0.433	0.521
Line2_15_to_29_mod.txt	39.4943	-119.866	415	0.183	0.374	0.804
Line2_15_to_44_mod.txt	39.5125	-119.812	486	0.393	0.52	0.184
Line2_16_to_30_mod.txt	39.4934	-119.867	415	0.233	0.373	0.707
Line2_16_to_45_mod.txt	39.5418	-119.713	263	0.178	0.385	0.521
Line2_17_to_46_mod.txt	39.5124	-119.811	486	0.393	0.52	0.184
Line2_18_to_47_mod.txt	39.5418	-119.712	263	0.178	0.385	0.521
Line2_19_to_48_mod.txt	39.5124	-119.81	525	0.433	0.433	0.13
Line2_1_to_13_mod.txt	39.5056	-119.864	382	0.395	0.918	1.098
Line2_20_to_49_mod.txt	39.5418	-119.71	264	0.17	0.315	0.448
Line2_21_to_50_mod.txt	39.5125	-119.809	525	0.433	0.433	0.13
Line2_22_to_51_mod.txt	39.5418	-119.709	264	0.175	0.308	0.448
Line2_23_to_52_mod.txt	39.5125	-119.808	525	0.37	0.37	0.13
Line2_24_to_53_mod.txt	39.5418	-119.708	264	0.175	0.308	0.448

File Name	Latitude	Longitude	Vs30 (m/s)	Z1.0 (km)	Z2.5 (km)	Zg (km)
Line2_25_to_54_mod.txt	39.5127	-119.806	554	0.37	0.37	0.13
Line2_26_to_55_mod.txt	39.5417	-119.707	264	0.143	0.258	0.448
Line2_27_to_56_mod.txt	39.5128	-119.805	554	0.37	0.37	0.115
Line2_28_to_57_mod.txt	39.5418	-119.706	267	0.158	0.258	0.372
Line2_29_to_58_mod.txt	39.5128	-119.804	565	0.373	0.373	0.115
Line2_30_to_59_mod.txt	39.5418	-119.705	267	0.148	0.235	0.372
Line2_31_to_60_mod.txt	39.5418	-119.704	266	0.136	0.204	0.372
Line2_4_to_18_mod.txt	39.5024	-119.865	382	0.345	0.805	1.043
Line2_5_to_19_mod.txt	39.5015	-119.865	401	0.263	0.62	1.043
Line2_6_to_20_mod.txt	39.5005	-119.865	401	0.323	0.603	0.975
Line2_7_to_21_mod.txt	39.5005	-119.862	401	0.418	0.56	0.975
Line2_8_to_22_mod.txt	39.4996	-119.862	401	0.288	0.56	0.975
Line2_9_to_23_mod.txt	39.4988	-119.862	382	0.25	0.53	0.975
Line3_11_to_25_mod.txt	39.5121	-119.861	395	0.205	0.688	1.089
Line3_13_to_27_mod.txt	39.5112	-119.857	395	0.185	0.733	1.084
Line3_14_to_28_mod.txt	39.5108	-119.854	395	0.218	0.675	0.973
Line3_15_to_29_mod.txt	39.511	-119.852	403	0.168	0.665	0.973
Line3_16_to_30_mod.txt	39.5117	-119.85	403	0.186	0.713	0.812
Line3_1_to_15_mod.txt	39.5096	-119.884	395	0.22	0.58	0.461
Line3_3_to_17_mod.txt	39.51	-119.88	403	0.25	0.588	0.595
Line3_6_to_20_mod.txt	39.5109	-119.873	395	0.205	0.67	0.842
Line3_8_to_22_mod.txt	39.5113	-119.868	395	0.205	0.69	0.991
LOVE.txt	39.5199	-119.806	450	0.117	>0.151	0.065
NMHS-RS.txt	39.53166	-119.777	370	0.11	>0.120	0.013
NMHS.txt	39.53155	-119.776	434	0.074	>0.200	0.013
NOAA-RS.txt	39.56819	-119.796	401	0.101	0.138	0
NOAA.txt	39.5681	-119.796	407	0.04	>0.150	0
PICO.txt	39.43036	-119.775	350	0.077	>0.200	0.176
RF05.txt	39.50946	-119.837	581	0.125	>0.200	0.495
RF08.txt	39.54262	-119.856	521	0.151	>0.200	0.197
RFMA.txt	39.51951	-119.901	436	0.096	>0.200	0.167
RFNV.txt	39.57392	-119.829	597	0.07	>0.150	0
SF02.txt	39.55564	-119.733	296	0.084	>0.150	0.086
SKYF-RS.txt	39.48209	-119.836	275	0.108	>0.122	0.253
SKYF_RF07.txt	39.48272	-119.835	337	0.102	>0.150	0.253
SPHI.txt	39.5438	-119.76	355	0.124	>0.200	0.431
SWTP-RS.txt	39.51574	-119.704	552	0.007	0.163	0
SWTP.txt	39.51592	-119.704	731	0.119	>0.301	0
UNRN.txt	39.5272	-119.819	376	0.099	>0.200	0.265
vrrt5-12.txt	39.47587	-119.672	620	0.025	>0.050	0.034
VSTA1-s1-remi.txt	39.5746	-119.829	664	0.032	>0.132	0
VSTA2-s2-remi.txt	39.5746	-119.829	833	0.036	>0.136	0

File Name	Latitude	Longitude	Vs30 (m/s)	Z1.0 (km)	Z2.5 (km)	Zg (km)
VSTA3-s7-remi.txt	39.5746	-119.829	533	0.03	>0.200	0
VSTA4-s2-remi.txt	39.5746	-119.829	526	0.026	>0.200	0
WTP-s6-remi.txt	39.5159	-119.702	623	0.041	>0.141	0
WYRD.txt	39.49228	-119.76	294	0.063	>0.200	0.569
Below from Las Vegas:						
transect2000A.txt	36.11343	-115.185	431	0.68	>0.400	0.41
transect2000B.txt	36.11125	-115.185	420	0.079	>0.400	0.39
transect2001A.txt	36.18891	-115.142	306	0.14	>0.240	1.71
transect2002A.txt	36.179	-115.149	389	0.048	>0.148	1.52
transect2002B.txt	36.17693	-115.149	391	0.07	>0.200	1.67
transect2002C.txt	36.17486	-115.149	409	0.033	>0.177	1.67
transect2100A.txt	36.10542	-115.186	467	0.1	>0.300	0.34
transect2100B.txt	36.10368	-115.186	441	0.118	>0.300	0.34
transect2100C.txt	36.10194	-115.186	423	0.046	>0.146	0.28
transect2101A.txt	36.15009	-115.165	498	0.193	>0.293	0.95
transect2101B.txt	36.14812	-115.166	510	0.122	>0.222	0.93
transect2101C.txt	36.14614	-115.168	577	0.124	>0.300	0.95
transect2102A.txt	36.15739	-115.16	458	0.133	>0.400	1.23
transect2200A.txt	36.13524	-115.179	661	0.088	>0.400	0.76
transect2200B.txt	36.13301	-115.18	571	0.102	>0.202	0.65
transect2200C.txt	36.13078	-115.181	529	0.097	>0.400	0.58
transect2201A.txt	36.14124	-115.174	494	0.101	>0.201	0.86
transect2201B.txt	36.13929	-115.176	524	0.109	>0.400	0.83
transect2201C.txt	36.13733	-115.178	537	0.127	>0.227	0.76
transect2202A.txt	36.14322	-115.173	400	0.121	>0.300	0.91
transect2203B.txt	36.12594	-115.186	580	0.251	>0.400	0.52
transect2203C.txt	36.12345	-115.186	439	0.17	>0.270	0.49
transect2300B.txt	36.21264	-115.128	567	0.093	>0.300	1.93
transect2300C.txt	36.2106	-115.13	503	0.111	>0.211	1.93
transect2301A.txt	36.1959	-115.14	286	0.118	>0.400	1.79
transect2301B.txt	36.19372	-115.141	229	0.097	>0.197	1.79
transect2301C.txt	36.19154	-115.142	302	0.099	>0.199	1.71
transect2400A.txt	36.2084	-115.131	454	0.152	>0.252	1.9
transect2400B.txt	36.20633	-115.133	363	0.144	>0.244	1.89
transect2500A.txt	36.20217	-115.136	299	0.209	>0.400	1.86
transect2500B.txt	36.2002	-115.137	327	0.114	>0.400	1.86
transect2501A.txt	36.12146	-115.19	484	0.074	>0.174	0.45
transect2501B.txt	36.11921	-115.19	454	0.038	>0.200	0.38
transect2501C.txt	36.11696	-115.19	436	0.064	>0.234	0.38
transect2502A.txt	36.16715	-115.155	477	0.125	>0.225	1.54
transect2502B.txt	36.165	-115.156	481	0.08	>0.180	1.35
transect2502C.txt	36.16285	-115.157	502	0.056	>0.222	1.28

File Name	Latitude	Longitude	Vs30 (m/s)	Z1.0 (km)	Z2.5 (km)	Zg (km)
transect2503A.txt	36.17255	-115.15	436	0.07	>0.170	1.71
transect2503B.txt	36.17082	-115.152	424	0.072	>0.200	1.71
transect2503C.txt	36.16909	-115.154	481	0.087	>0.187	1.54